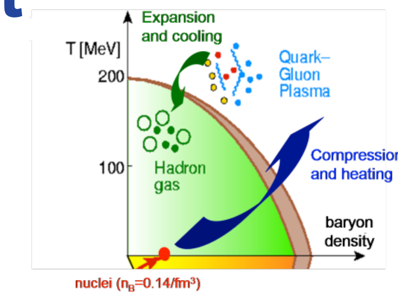
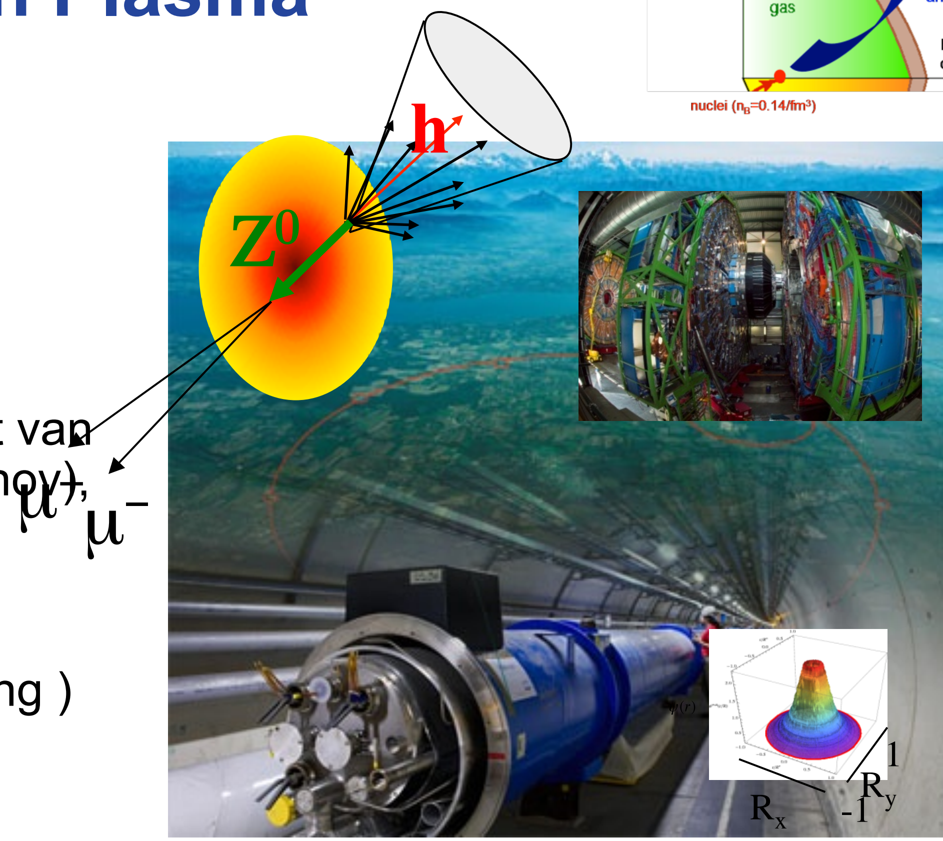
First Unambiguous Measurement of Jet Fragmentation and Energy Loss in the Quark-Gluon Plasma



P-25, P-23 and T-2

A new direction of research at LANL



Gerd J. Kunde, Melynda Brooks, Hubert van Hecke, Pat McGaughey, (Camelia Mironov), Catherine Silvestre

Andi Klein

Bryon Neufeld, Ivan Vitev, (Benwei Zhang)

F. Wilczek (Nobel Laureate NewScientist, 2006) : “Fundamental physics … will experience a *new golden age, catalyzed by the LHC*.”

Los Alamos NATIONAL LABORATORY EST. 1943

Physics & T division

Presentation Outline

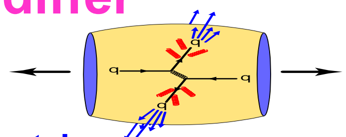
- The nuclear modification factor R_{AA}
- The ratio of fragmentation functions (LDRD-ER)
- Endorsements and reviews
- The CMS experiment and first results on dimuons
- LANL and CMS
- Analysis and technical contributions
- 5 year plan - NSAC milestones
- Achievements

Success and Limitations of QGP Studies at RHIC

PHENIX @ RHIC

- **Evidence** that QGP can be created in Heavy Ion Collisions

Extracted QGP densities differ up to a factor of ~10 !



- **Pressing questions**: What is, quantitatively, the nature of Matter in Extremis? **What is the Equation-of-State of the Quark Gluon Plasma ?**

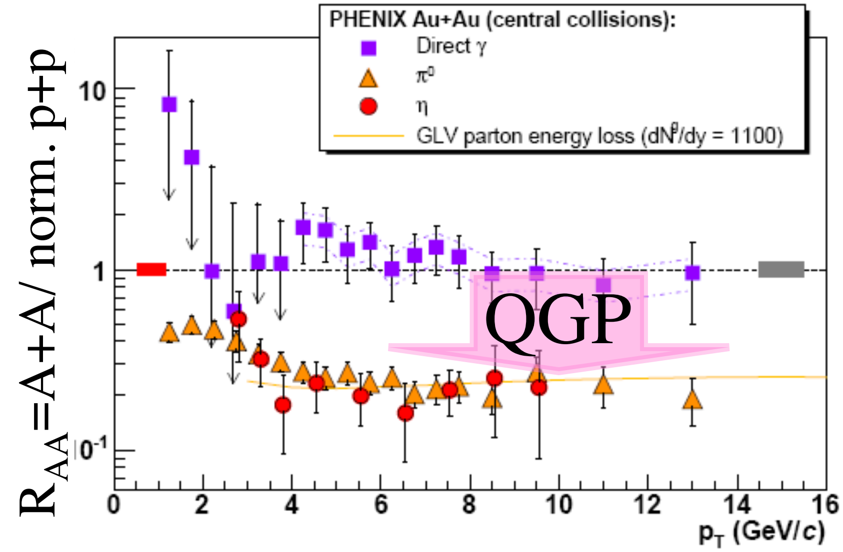


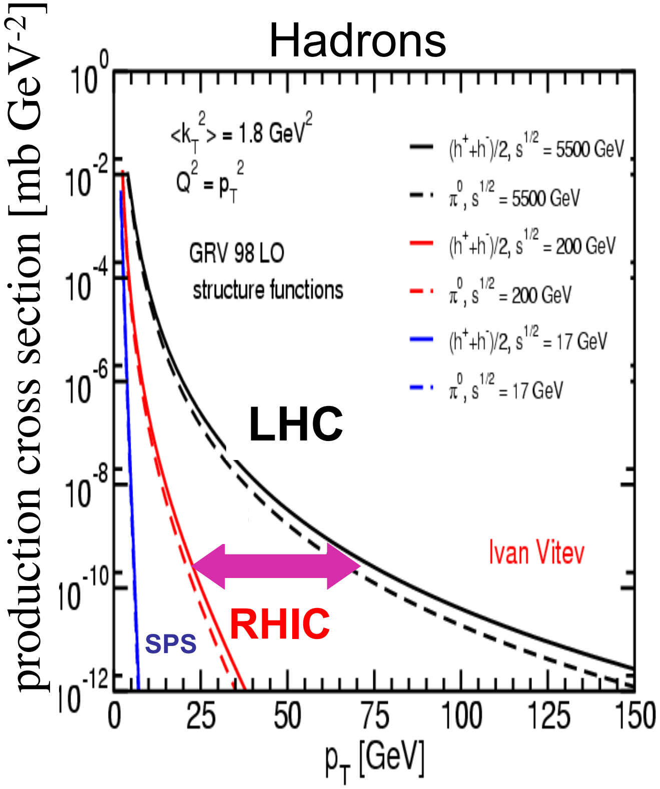
FIG. 3: $R_{AA}(p_T)$ measured in central Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

Measurements at RHIC, just like R_{AA} , are inclusive: they integrate over many initial states and mechanisms

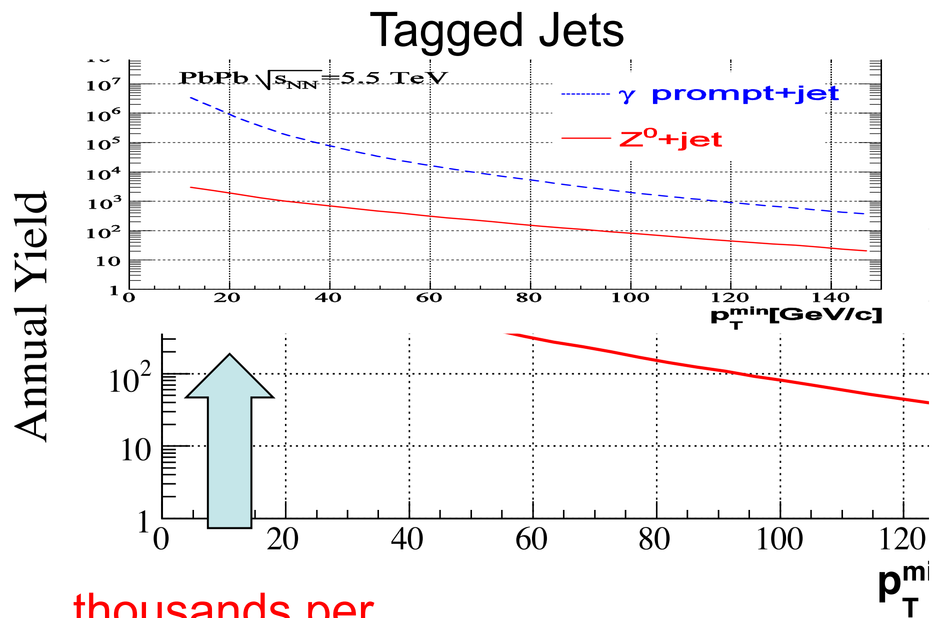
Need to add data from LHC → exclusive jets, tagged jets, ultimate detector

DM 10 (2014) Measure jet and photon production and their correlations in A≈200 ion+ion collisionsat energies from medium RHIC energies to the highest achievable energies at LHC.

Future Heavy Ion Physics with Hard Probes



Enormous increase from RHIC to LHC for hard probes



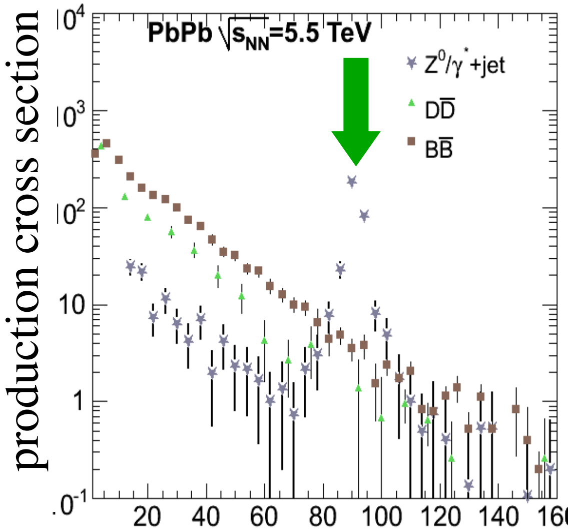
thousands per year

- High cross sections for hard probes at LHC
- CMS detector at LHC ideally suited for electromagnetic tagging of whole jets
- LDRD-ER 2006 pioneered Z^0 tagging
- LDRD-ER 2009 measures Z^0 production in PbPb

Unique Jet Tagging – LDRD ER (2006)

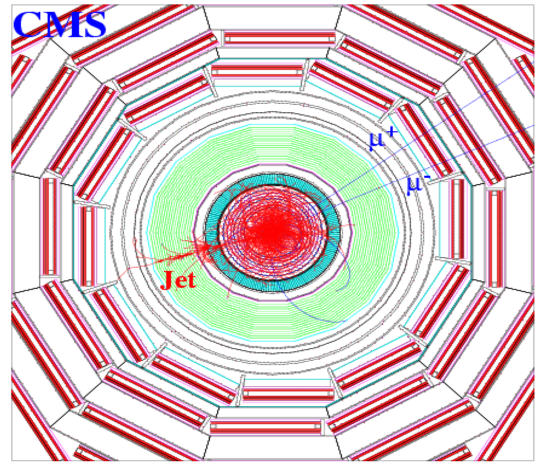
PI G.J.Kunde

Simulation 1month Pb+Pb

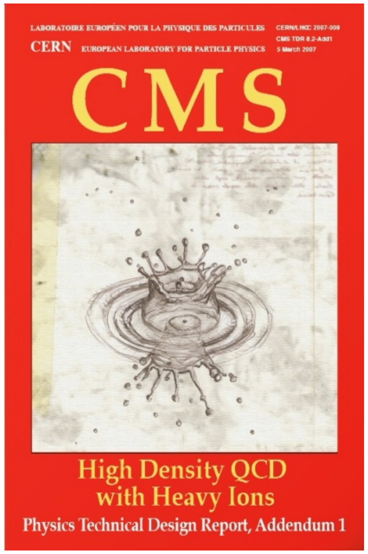


Simulation Z + Jet

dNch / dY = 5000

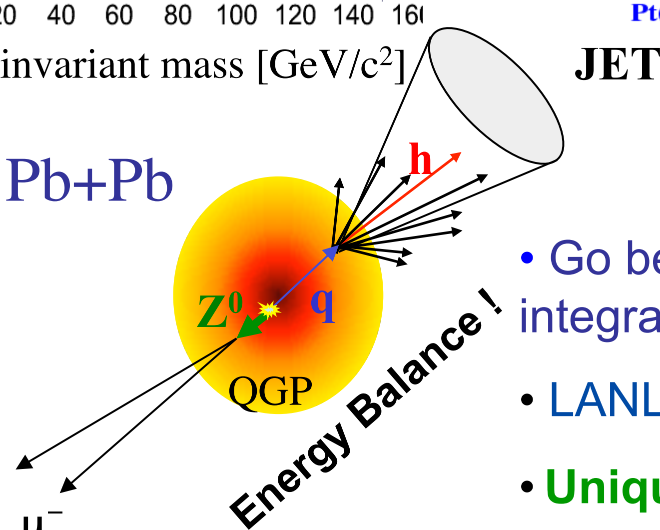


Pt(Z) = Et(Jet) = 100 GeV.



J. Phys. G: Nucl. Part. Phys. 34 (2007)

C. Mironov is Co-editor



- Go beyond inclusive RHIC measurements which integrate over many initial states ➡ **select initial state**
- LANL LDRD-ER 06 established jet tagging with Z^0
- **Unique Advantage:**
  - **Measures initial jet energy directly ! (LO)**

The Ratio of Fragmentation Functions

We propose to replace the Nuclear Modification Factor R_{AA}

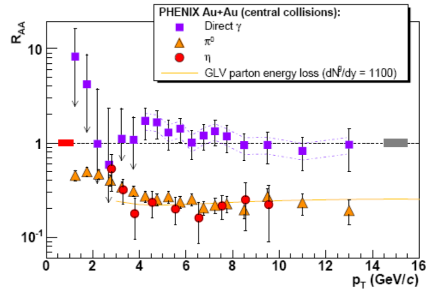


FIG. 3: $R_{AA}(p_T)$ measured in central Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

by

Eur. Phys. J. C (2009) 61: 785–788 787

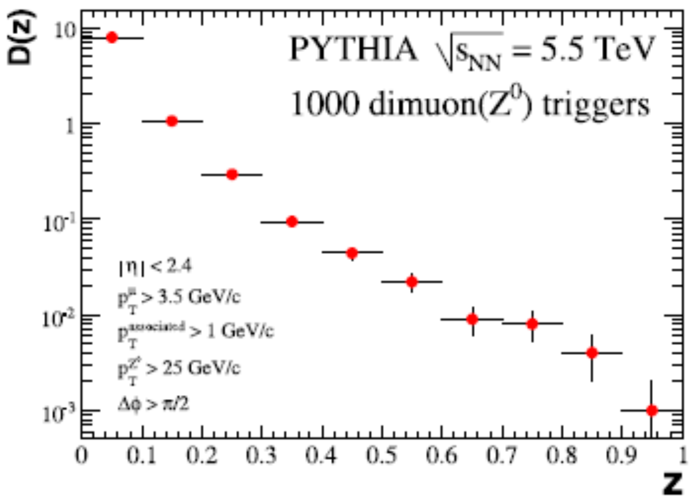


Fig. 6.1 Fragmentation Function $D(Z)$ as determined from the reconstruction of correlated hadrons. The statistical error bars reflect a year-one measurement

Fragmentation Function

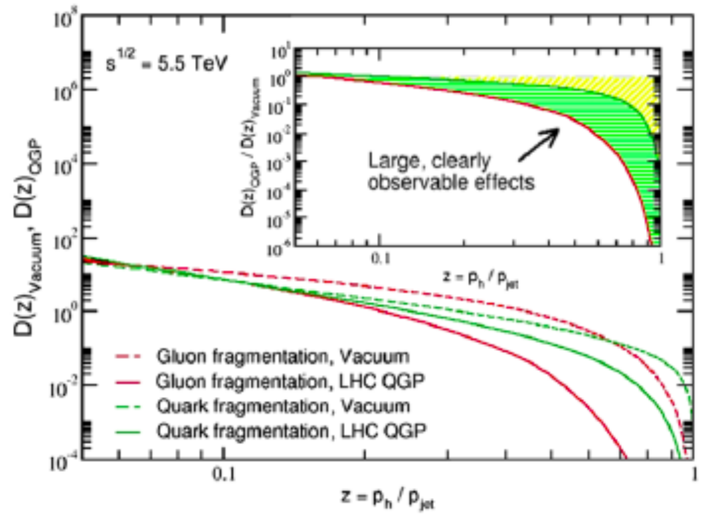


Fig. 6.2 Fragmentation Function $D(Z)$ for quarks and gluons in the vacuum and in a LHC QGP. The fragmentation results for the vacuum case are represented as dashed lines, the QGP result is shown as sold lines. The insert shows the ratio of the fragmentation functions for QGP vs. vacuum. Please note the logarithmic representation

Ratio of Frag. Functions

High Energy / Nuclear Physics Requests LANL Participation at the LHC - Letters in support of LDRD

"I find this to be an outstanding proposal which incorporates a number of novel ingredients; the combination has the potential to make a significant impact on the field by providing a systematic description of QGP in extreme conditions, as well as contributing to the broader LHC discovery program."

Fred Olness, CERN and SMU, LHC theory collaboration (ATLAS member)

We have been encouraged to join CMS for our intellectual leadership and technical skills!

"In summary, the CMS HI group would benefit tremendously from the participation of LANL physicists. The LANL group has extensive experience in extracting exciting physics from hadronic and nuclear interactions. Their particular strength is the area of jet physics and quarkonium where CMS wants to make the biggest discoveries."

Bolek Wyslouch, MIT, Project Manager for the US CMS Heavy-ion collaboration

"The participation of this group, which is experienced in the R&D and implementation of these kinds of advanced detectors, will certainly be crucial …."

Joel Butler, Fermilab, US CMS Research Program manager

The Project in Reviews

- "Mike Turner"- Review of the LDRD program (2008)
  - Very positive: LDRD responded with increase in funding (3x) and startup money.
- DOE Nuclear Physics Review of CMS program (2009)
  - Report:
    *In summary, the CMS HI Collaboration has provided the review panel complete and satisfactory responses to the scientific questions resulting from the 2006 DOE review of the original CMS HI proposal. The scientific merit of the proposal remains strong, and the feasibility of measuring high energy jets, **Z0,** and upsilon detection in the muon decay channel at mid-rapidity was demonstrated.*

    Review excerpt:
    *The physics of nuclear collisions at the LHC is expected to be dominated by hard processes. Jets will be abundantly produced and their study will likely lead to a deeper understanding and scrutiny of the jet quenching phenomena discovered at RHIC. The CMS detector with its nearly hermetic acceptance is specially suited for the study of jets. In particular, the large coverage of its calorimeters and muon tracking system at mid-rapidity will allow the study of high energy jets. The calorimeters will allow the study of direct gamma+jet or **Z^0+jet coincidences** in the cleanest possible way where a direct photon or a Z^0 is detected in the calorimeter, **providing an unbiased measurement of the initial jet energy whereas the recoiling jet is used to probe the medium.***

Letter of Endorsement from CMS Heavy Ion Program Manager Bolek Wyslouch from MIT

Boleslaw Wyslouch
Professor of Physics

Massachusetts Institute of Technology
77 Massachusetts Avenue, Building 24-518
Cambridge, Massachusetts 02139-4307

Phone (617) 253-5431
Fax (617) 253-1755
Email wyslouch@mit.edu

August 4, 2010

Dr. Melynda Brooks,
Heavy Ion Group Leader
Los Alamos National Laboratory

Dear Melynda,

I understand that Los Alamos is conducting the internal review of the future group plans. I was talking to Gerd Kunde recently about his plans for contributions to CMS Heavy Ion program. As you well know I am very supportive of the participation of Los Alamos in our program and I understand the need of developing a strong program where the laboratory could make significant contribution. While the physics program of Los Alamos is clear with emphasis on jets and muons the "hardware" contribution is less obvious.

Over the last year or so Gerd, Ivan Calo, Andi and others have made significant progress in understanding the functioning of CMS pixel detector. There are indications that CMS may run into difficulties related to memory buffer overflows, especially during the high intensity HI beams expected in 2013 and beyond. In fact, already this year, we will follow Gerd and Ivan's suggestions and introduce a special trigger hold-off to prevent memory issues.

Gerd, together with the Pixel group is thinking about proposing a memory upgrade, together with new firmware. Such changes require significant development work and highly skilled expertise. One could easily imagine proposing and executing a project, specifically to improve CMS capability in reading out heavy ion data and to be ready for 2013 run. The present work on test board and the actual running experience we hope to get in the HI run this November will make it possible to propose official participation of LANL to DOE NP early next calendar year. Such project would have to be managed carefully within CMS and coordinated with the parallel plans to upgrade pixel detector for high luminosity pp running. We do not have anyone else in the heavy ion group who has enough knowledge to deal with this potentially very difficult issue.

I am very enthusiastic about the opportunity of continuing participation of Los Alamos in the CMS HI program and I would be happy to support your efforts to get funding from DOE NP.

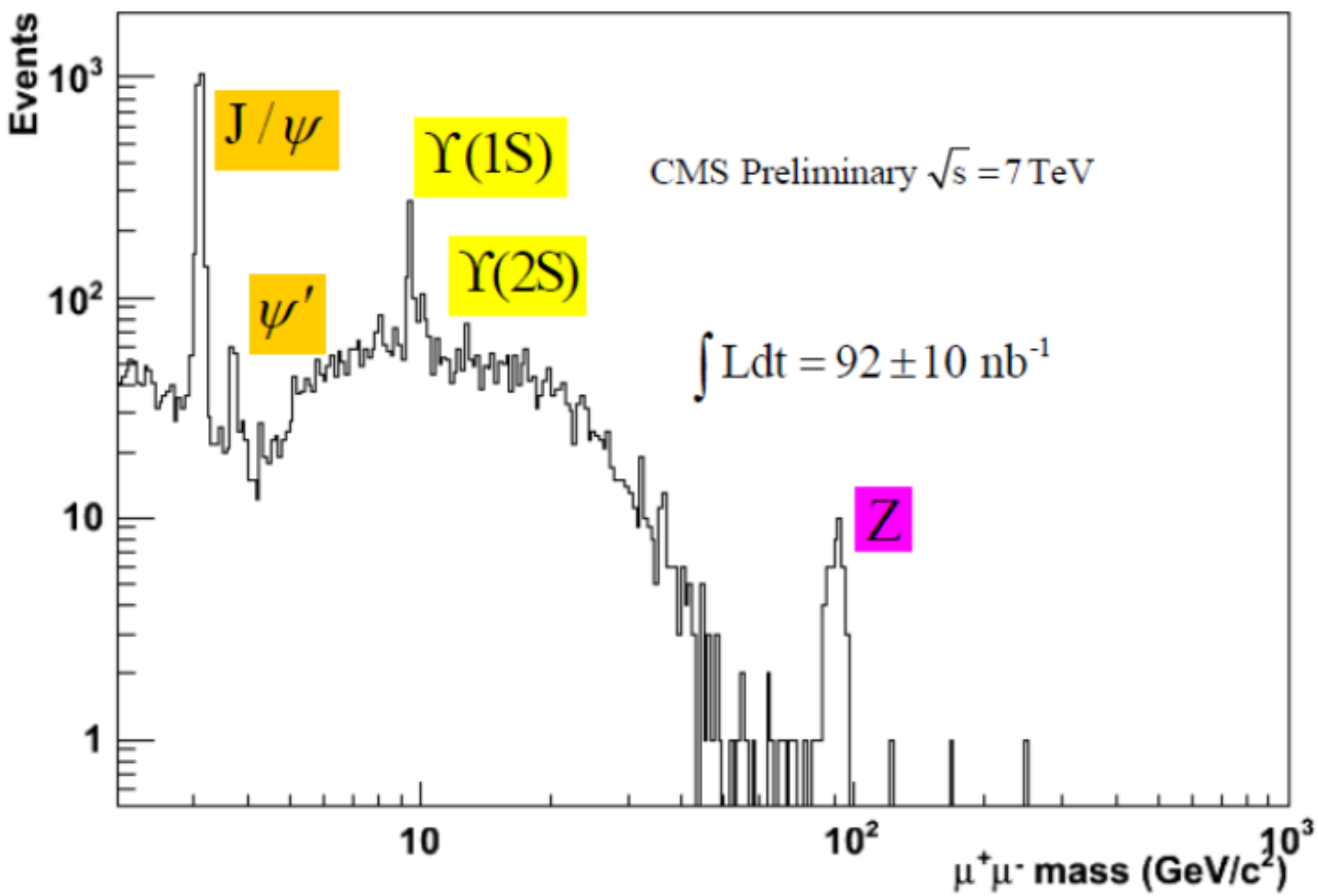
Yours Sincerely

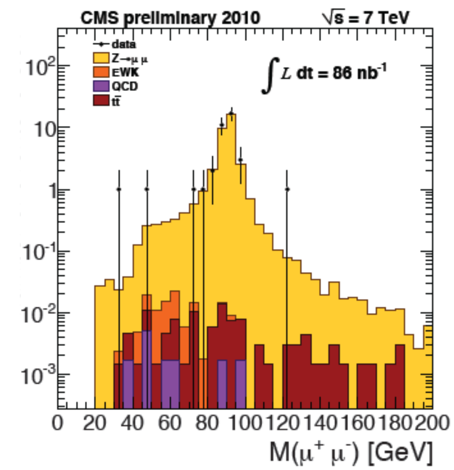
Bolek Wyslouch

Boleslaw Wyslouch
Professor of Physics
US CMS Heavy Ion Program Manager

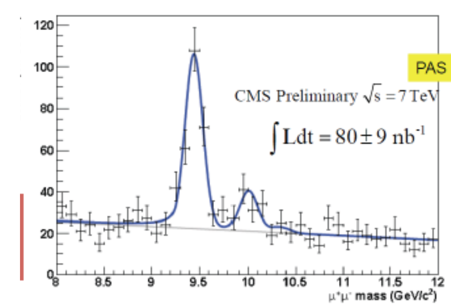
- "As you well know I am very supportive of the participation of Los Alamos in our program."
- "Gerd, together with the Pixel group is thinking about proposing a memory upgrade, together with new firmware. Such changes require significant development work and highly skilled expertise."
- "We do not have anyone else in the heavy ion group who has enough knowledge to deal with this potentially very difficult issue."
- "I am very enthusiastic about the opportunity of continuing participation of Los Alamos in the CMS HI program and I would be happy to support your efforts to get funding from DOE NP."

Why We Want to Work in CMS in One Slide – REAL pp DATA !





σ(pp→Z+X→μμ+X) = 0.94 ± 0.16 nb



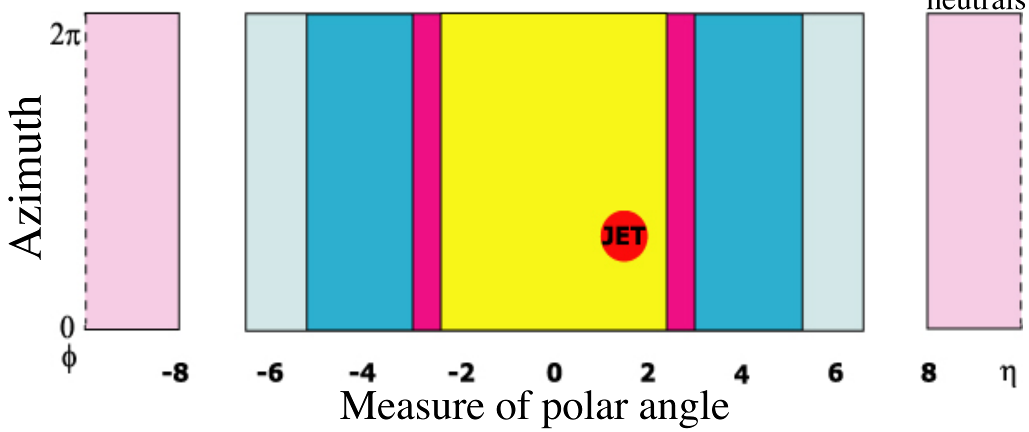
9.7+-0.9+-1.1+-1.6 nb

The ultimate dimuon detector with a coverage of nearly 5 units of rapidity (with Si tracking)

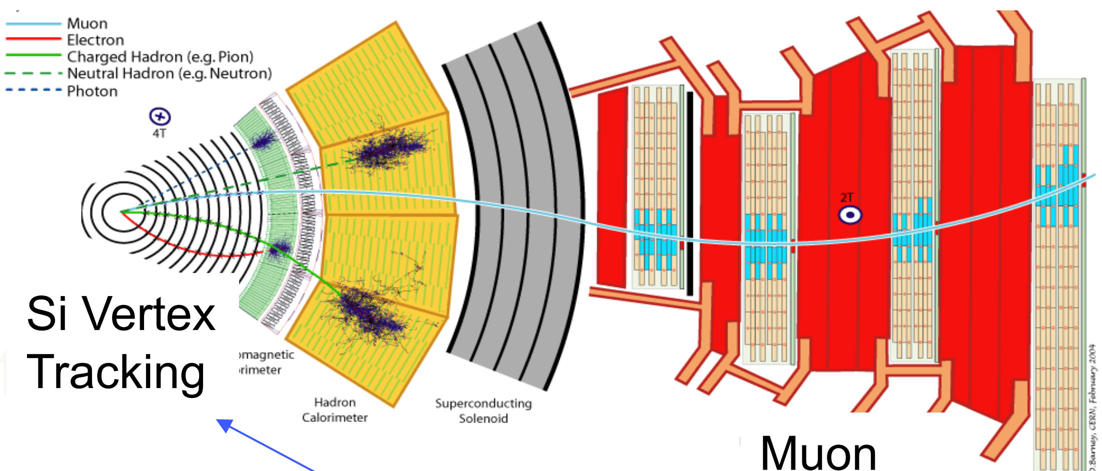
&

CMS - The Ultimate Detector for HI Physics with Jets

CMS Acceptance



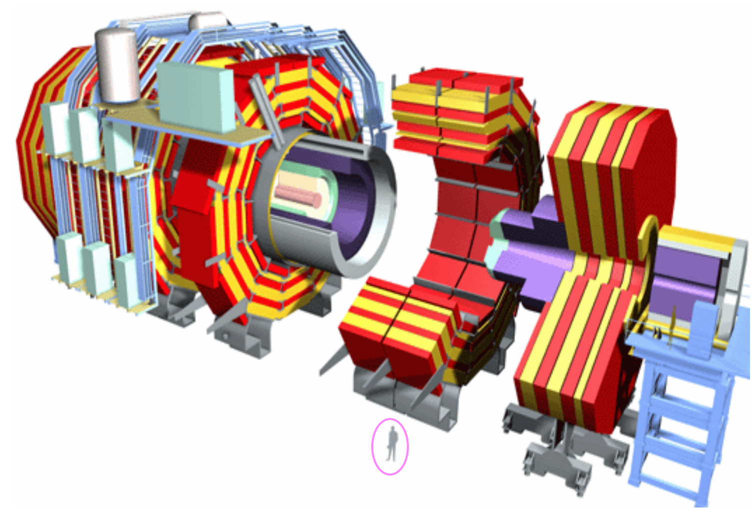
Acceptance and Particle Detection



Si Vertex Tracking

Muon Tracking

Compact Muon Solenoid



- Excellent Jet Calorimetry
- Best Muon Detection

  Z^0 measurement + Quarkonia
- Best Vertex Tracking

  Jets via tracks – 3.8 Tesla field

LANL Expertise

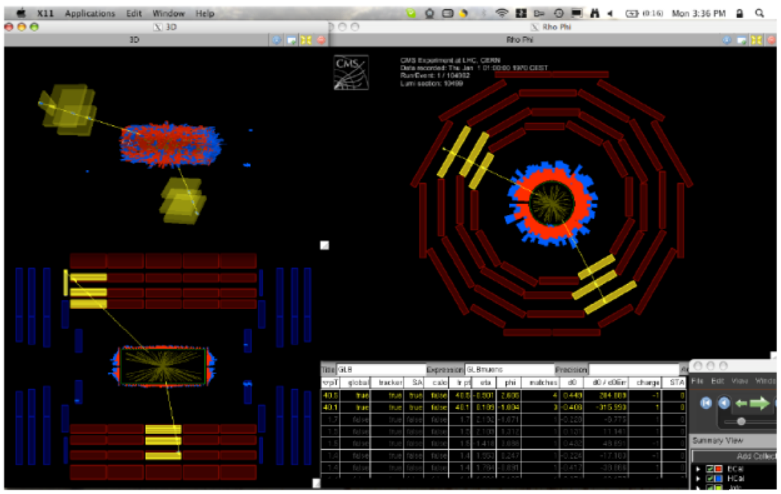
FVTX and PHENIX Muon Detectors

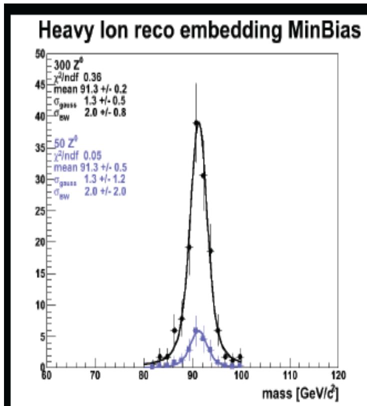
LANL in CMS-Heavy Ion

- Gerd J. Kunde
  - Leads the LANL Pixel Frontend Driver project
  - Champions the pixel detector in the HI detector readiness reviews
  - Gives invited international plenary talks for CMS
  - Organized 1st and 2nd annual CMS Heavy Ion Workshop in Santa Fe
- Catherine Silvestre-Tello
  - Convener of the dilepton Physics INterest Group (there are 5 groups)
  - Analysis: Z^0 Embedding and Signal Extraction
  - Champions the muon detectors in the HI detector readiness reviews
  - Gives invited international talks for CMS
- (Camelia Mironov)
  - Co-Editor of TDR
  - Analysis: Z^0 + jet - generator level
  - Organized Special CMS HI Tracking Meeting 2008

The Z^0 in the Mock Data Challenge July 2010

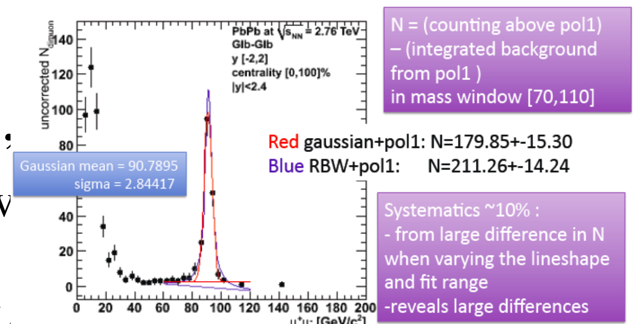
July 14th fireworks!

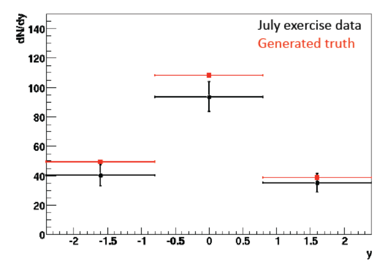


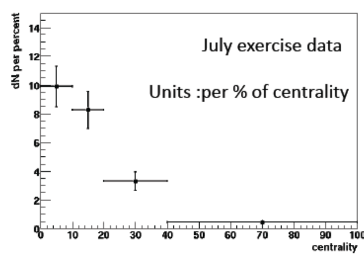


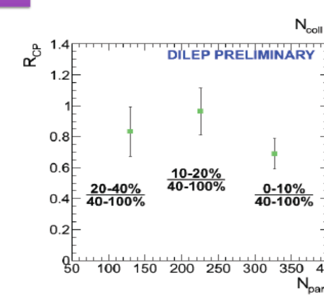
- First planned di-muon paper for HI
- Work on pp reference underway
- Measurement will use all available statistics
- Expect few dozen to few 100Z^0s
- If min bias pre-scaled, use L1 dimuon trigger
- First Z^0 measurement in HI
- (Future: Z^0+Jet)

- First Paper will be on Z^0 cross sections in Heavy Ions, first measurement ever (w aligned with LDRD)
- Follow up papers will be J/ psi and Upsilon (fits our research interest very well)









The Pixel Readout Chain and the Bottle Neck for Design Luminosity Data Taking

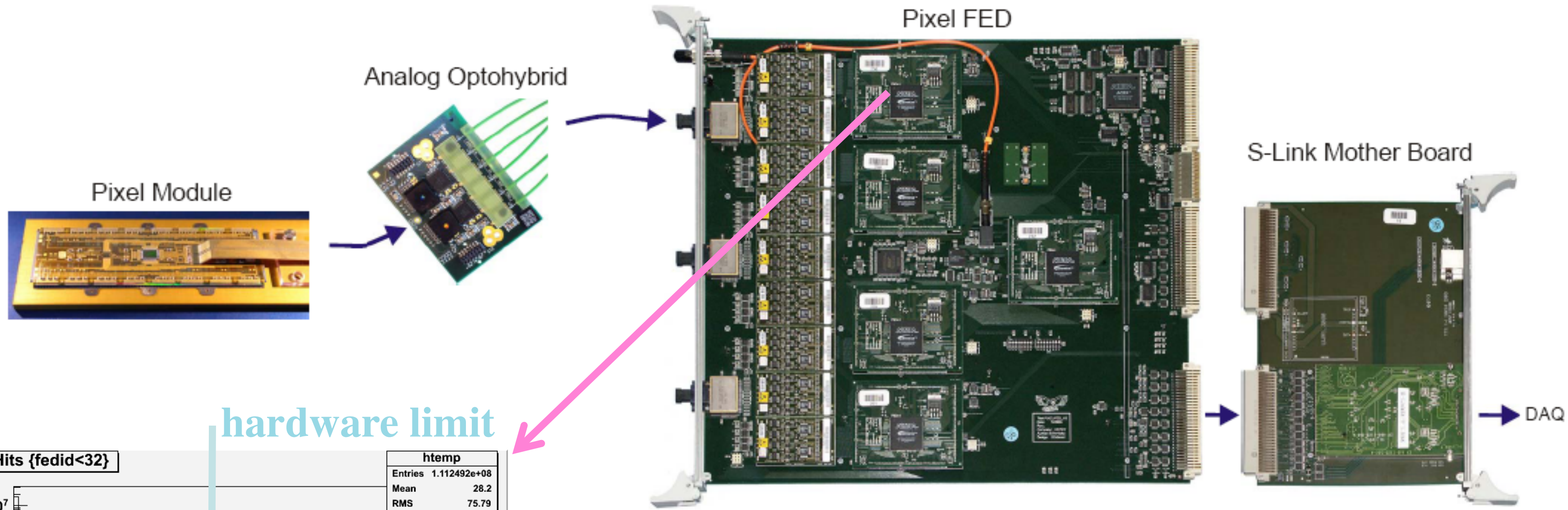
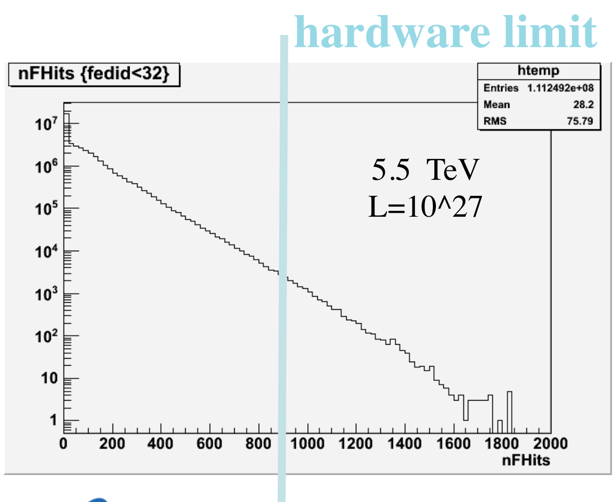
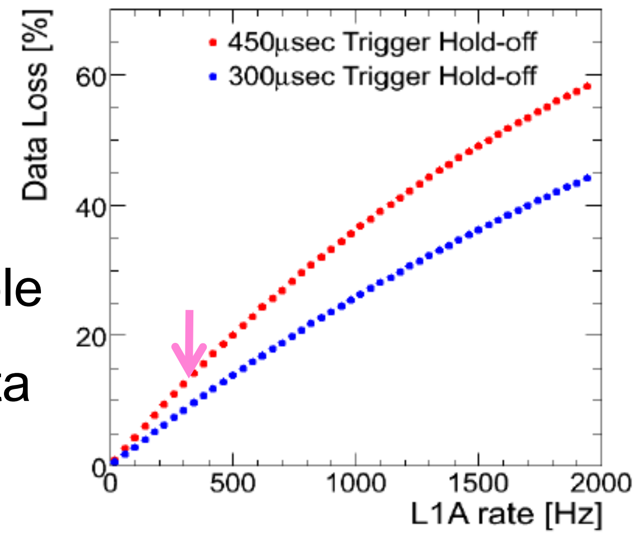


Figure 1: The Pixel Detector Readout Chain



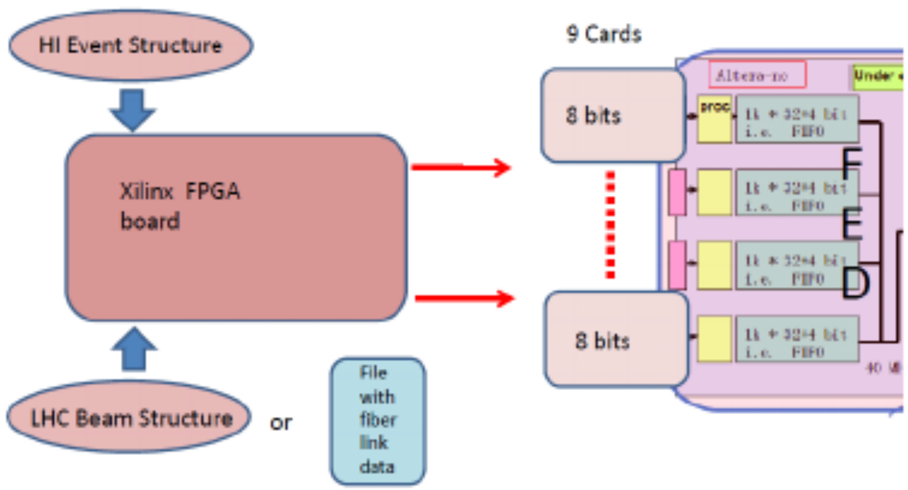
- Fifo I overflows occur with an average rate of ~600/ sec
- Constructed a temporary fix for low luminosity HI running by introducing a dead time of 400 micro seconds (CMS was designed to be dead time free)

Solving the Pixel Readout Issues



- Introduced and tested a dead time for the whole experiment – while it enables year 1 and 2 data taking, it will not work for design luminosity
- CMS Heavy Ion relies on using a High Level Trigger to reduce 8000 Hz min bias via sophisticated algorithms to 200 Hz archiving, needs minbias Level 1 !
- Conceived, developed and are constructing the Pixel Frontend Driver to test/develop the Pixel FED readout in the 11 month there is no beam
  - First test in September with Geant4 based CMSSW Monte Carlo results with dN/dy of 2500
  - Future tests with measured link multiplicities from year one

The LANL Pixel Frontend Driver

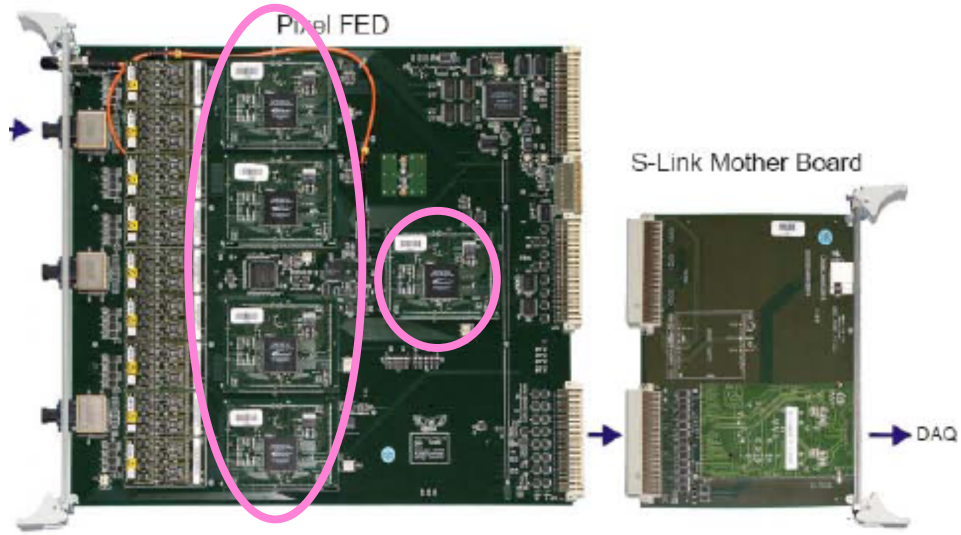


- Replace the fiber translators with serial receivers for FGPA driven HI events with realistic time structure

- Pat : Design of the Spartan board and all interface cards
- Andi: VHDL code for Virtex 6, Testing
- Gjk: Overall design, VHDL for Spartan, Testing

Towards a Technical Solution by LANL

- There are 36 * 4 Fifo I mezzanine boards
- There are 36 FIFO III mezzanine boards



- LANL is leading the development for a solution of the FED problem to enable full usage of the HLT for Heavy Ion running
  - Hardware and firmware upgrades (bigger FPGAs)
  - Implementation parallel readout by Vienna (no longer a sequential data format – difficult) ?
  - Data Flow simulations and PFD test with new FIFO I firmware
  - First Heavy Ion run to measure Fiber Link Multiplicities
  - Pixel Group and Collaboration Feedback/ Pixel Upgrade Plans

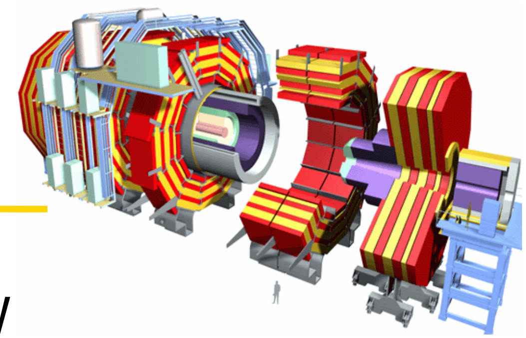
Funded ER2009 (ends FY11) and DOE Proposal

First Unambiguous Measurement of Jet Fragmentation and Energy Loss in the Quark-Gluon Plasma

- Measurement of jets tagged by Z^0s at the Large Hadron Collider (LHC).
- Concurrently develop the supporting perturbative many-body Quantum Chromo-dynamics (QCD) theory.
- First time reconstruction of the full jet fragmentation function and its in-medium modification.
  - Fragmentation functions describe the probability of a quark or gluon to produce a given momentum final state hadron.
- New data will severely constrain the current theoretical models of jet energy loss and thus allow for a precise determination of the plasma properties.

Transition to DOE Funding: two half staff and two post-docs

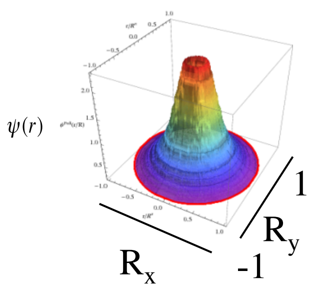
Physics Analysis Methods (ER)



- Analysis package for dimuons developed in CMSSW
  - C++ and python software that finds global muon tracks, determines the invariant mass of resonances and computes efficiencies based on physics Monte Carlo and detailed detector simulations .
  - Software will be used to determine Z^0 cross sections as soon as there is first data.
- Mock data challenge for Z^0 measurement
  - LANL convener led a successful physics extraction
- Analysis package for transverse energy under development
  - We developed the idea of this important basic measurement and are developing in CMSSW the packages that uses silicon detector tracks and electromagnetic calorimeter measurements to determine Et.
- MC simulation of front end driver electronics under development
  - We developed a Monte Carlo simulation that produces event files for FPGA simulations of the front end driver performance

  - LANL showed that there is a memory problem in the pixel FED

Technical Methods and Synergy with Theory (ER)



- Developing the Pixel Frontend Driver and solution to the pixel readout problem
- Jet shapes and cross sections at the LHC are calculated using Perturbative QCD for p+p and Pb+Pb collisions
  - Energy loss of strongly interacting particles is obtained using the Gyulassy-Levai-Vitev formalism
- Parton distribution and fragmentation functions are calculated in factorized Perturbative QCD
  - Thermal quark-gluon plasma effects are taken into account.
  - Parton distributions become narrower in momentum space. There is little to no change in the fragmentation shape.
- The physics of Z^0/Y^*tagged jets at the LHC
  - NLO calculation of energy balance

Proposal for DOE Funding starting FY2012

- Ask to continue on DOE funding at current LDRD level:
  Two ½-staff and one physics and one technical postdoc
  - To capitalize on early ER which developed the Z0 tagging idea
    - 3 years of 150k
  - To capitalize on current ER which will measure Z0 cross sections in AA
    - 3 years of 500k
  - To capitalize on our FED readout expertise and by then developed solution
  - To capitalize on LANL Theory (Ivan's papers) !!
  - **To solve the pixel readout problem and to fully enable the HLT**
  - **To measure the ultimate probe for the QGP opacity**
    - **Z^0 tagged Jets in Heavy Ion Collisions**
    - **Jet Shapes**

- Bolek's thoughts :
  - "[ ] shooting for funding in FY12 may be realistic. I think that starting the discussion asking of two half time staff and two postdocs would be good"

Physics Analysis and Technical Plan

Year	Physics	Technical
FY10	Z^0 data challenge	Pixel Front Driver
FY11 (first run)	Z^0 cross section Jet shapes	Link multiplicities Proposal of solution + prototype
FY12 (second run)	Z^0 and Ypsilon R_{AA} Jet Shapes	Design and construction of solution
FY13 (shutdown)	Complement RHIC results with d/b from LHC	Implementation and testing of solution
FY14 (first design run)	Z^0 tagging of jets new physics ??	
FY15 (second design run)	Ratio of tagged fragmentation functions (Z^0 and b)	

DM 10 (2014) Measure jet and photon production and their correlations in A≈200 ion+ion collisions at energies from medium RHIC energies to the highest achievable energies at LHC.
DM12 (2016) Measure production rates, high pT spectra, and correlations in heavy-ion collisions at$\sqrt{s_{NN}}$ = 200 GeV for identified hadrons with heavy flavor valence quarks to constrain the mechanism for parton energy loss in the quark-gluon plasma.

Papers/ Talks/Hires

- Recent Papers
  - C. Mironov, M. Castro, P. Constantin, G.J. Kunde, R.Vogt, Int.J.Mod.Phys.E16:1950,2007.
  - C. Mironov, P. Constantin, G.J. Kunde, Eur.Phys.J.C49:19-22,2007.
  - C.Mironov, R.Vogt, G.J.Kunde, Eur.Phys.J.C61:893,2009.
  - G. J. Kunde, H. van Hecke, K. Hessler and C. Mironov, Eur.Phys.J.C 61:785,2009.
  - Hot Quark Proceedings (CST, in preparation)
  - INPC Proceedings (GJK, in preparation)

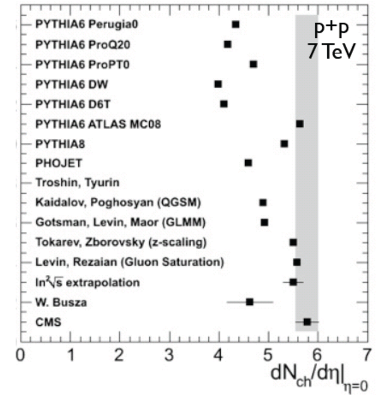
- Recent Invited Talks
  - Gerd J. Kunde:
    - Lecture Series at *Universidade de Coimbra*, Portugal 2009
    - Lecture Series at *Universidad Técnica Federico Santa María* Valparaiso,Chile 2010
    - **CMS plenary talk at Strange Quark Matter 2009 in Brazil**
    - **RHIC plenary talk at HEP2010 in Chile**
    - **CMS overview talk at INPC2010 in Canada**
  - Catherine Silvestre Tello
    - **Etretat09: Rencontres QGP-France 2009**
    - **Hot Quarks 2010 Workshop in France**
    - **EMMI Quarkonium Workshop 2010 in Italy**

- **Hires**
  - Camelia Mironov was awarded the Marie Curie Fellowship (2010)
  - Catherine Silvestre Tello will start INRS permanent position in 2011)
  - About to hire Torsten Dahms (CERN Fellow)

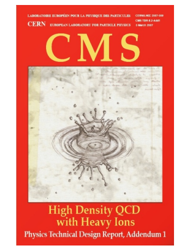
People working on and interested in CMS

- Gerd J. Kunde
  - Hard probes and pixel hardware
- Catherine Silvestre Tello
  - Hard Probes and dimuon analysis
- Andreas Klein
  - Computing, VHDL and pixel hardware
- Pat McGaughey
  - Quarkonia and pixel hardware
- Hubert van Hecke
  - Dimuons and Pythia
- Mike Leitch
  - Quarkonia
- Melynda Brooks
  - Quarkonia and VHDL

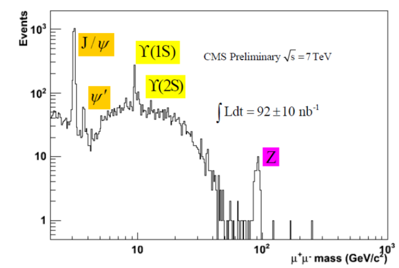
Summary



- Exciting new energy frontier at the LHC
  - What discoveries will we make ?

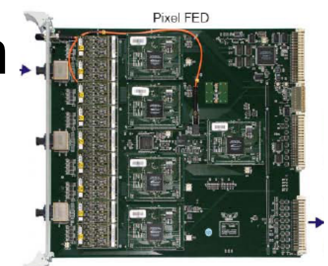


- Pioneered qualitatively new probe to study the QGP
  - Z^0 tagged jets



- Fantastic dimuon performance of CMS
  - Z^0 cross section already with 100 nb^{-1}

- LANL is in the position to enable the HLT for high luminosity Heavy Ion running
  - Solving the memory problem in the pixel FED



- **We have the endorsement and support of the US CMS Heavy Program manager to talk to DOE now**

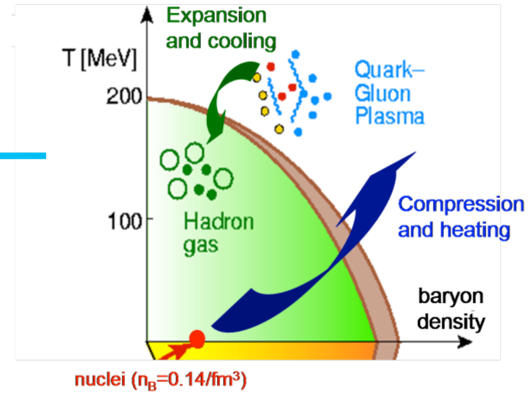
Backup Slides

- QGP Intro
- Barnes Report
- 2 slides on extracting the transport coefficient
- DOE/LANL Mission
- Background/Significance
- Analysis Methods
- Technical Methods
- Results

Results and Accomplishments

- Local computing server with CMSSW package installed
- Grid computing started (access to Tier 2 and 1 of CMS)
- Analysis package for dimuons developed/ Delivered dimuon tracking efficiency measurements to CMS
- Developed new important idea for year one Et measurement /Analysis package for transverse energy under development
- Developed MC simulation of front end driver electronics
- Developed/build and programmed in VHDL the pixel frontend driver
- Developed concept for the solution for the pixel readout problem
- Gave 2 out of 8 (muon and pixel) presentation at the HI Detector readiness review
- Convener of dilepton group in CMS HI
- Successful mock data challenge in July 2010 for Z^0 reconstruction !
- Organized first (2009) and second (2010) US CMS Heavy Ion workshop in Santa Fe
- Represented CMS at international meetings

Introduction – The QGP



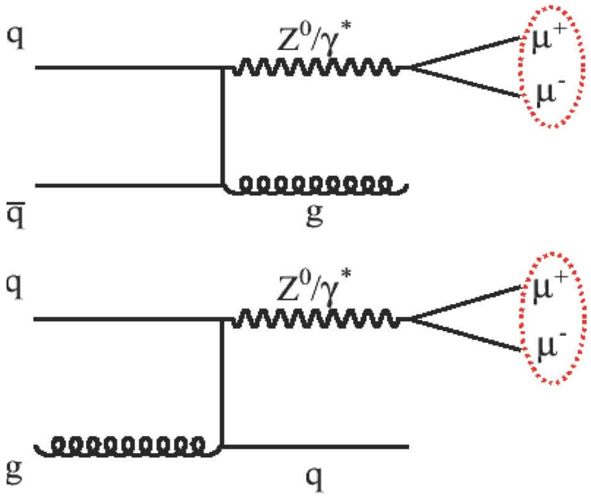
- The quark-gluon plasma (QGP) was discovered at the Relativistic Heavy Ion Collider (RHIC).
- QGP properties are not yet well understood. Specifically the strength of partonic energy loss is rather theory dependent because the measurements are not differential enough. Currently the extracted values for energy loss have a range of about a factor of 10.
- The Large Hadron Collider (LHC) will provide higher energies and therefore higher cross sections for hard probes. We proposed to make a first ever measurement of jet fragmentation with tagged jets (a hard probe) in the Compact Muon Solenoid Experiment (CMS).
- We will develop the theory of jet fragmentation and propagation of partons in the quark-gluon plasma.
- We expect that this combined experimental and theoretical effort will yield an accurate measurement of the energy loss and help determine the QGP opacity.

The Diagrams for Jet Tagging and the Monte Carlos

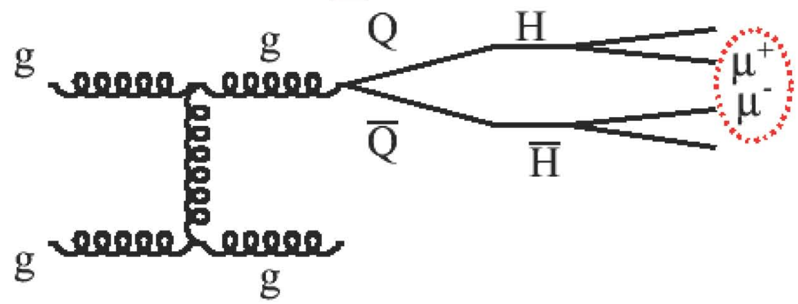
Pythia 6.32

HVQMNR

Z^0/γ^* + jet



$Q\bar{Q}$ background



- Jet-dilepton diagrams are the NLO correction to LO DrellYoung diagrams

- Given dilepton mass M, the DY cross section decreases exponentially, while the dilepton-jet cross section decreases like a powerlaw.

Z-tagged quark jets

Eur. Phys. J. C (2009) 61: 785–788
DOI 10.1140/epjc/s10052-009-0955-9

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Z^0-tagged quark jets at the large hadron collider

G.J. Kunde[a], H. van Hecke, K. Hessler, C. Mironov
Physics Division, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87506, USA

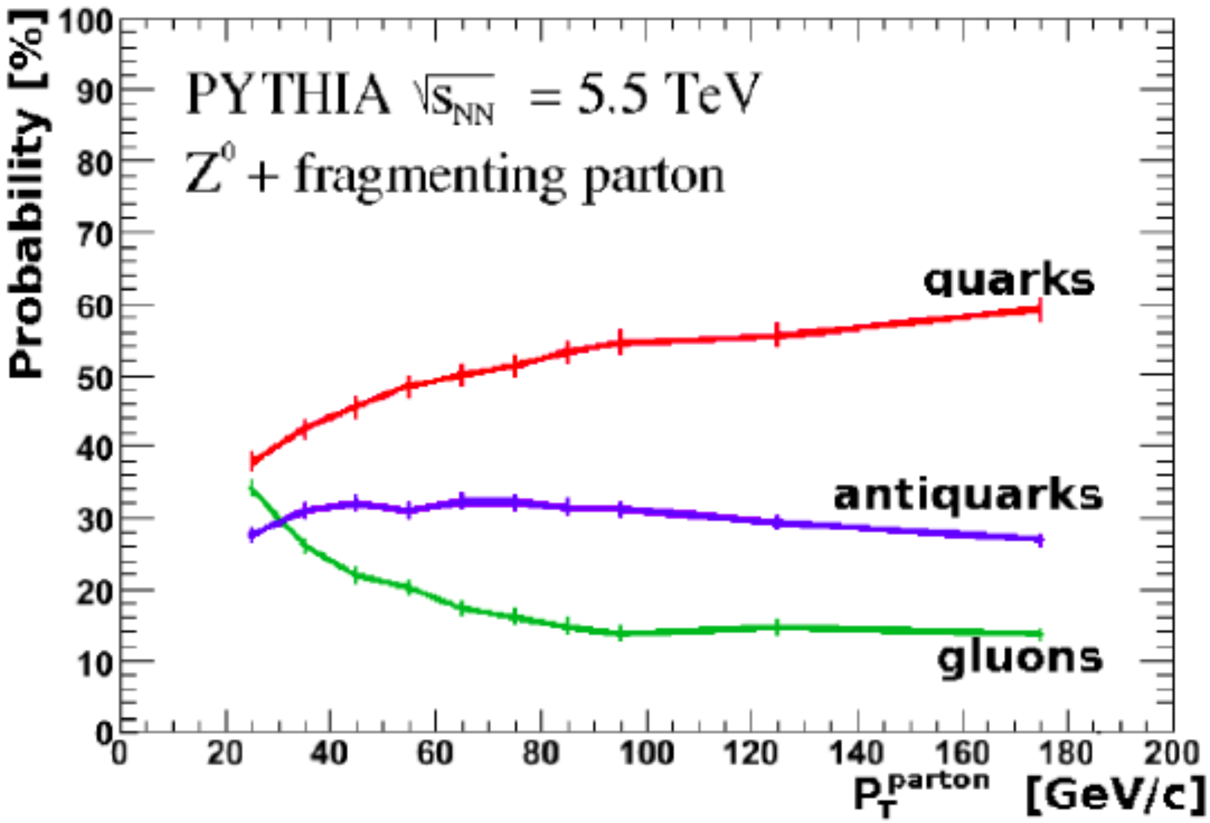
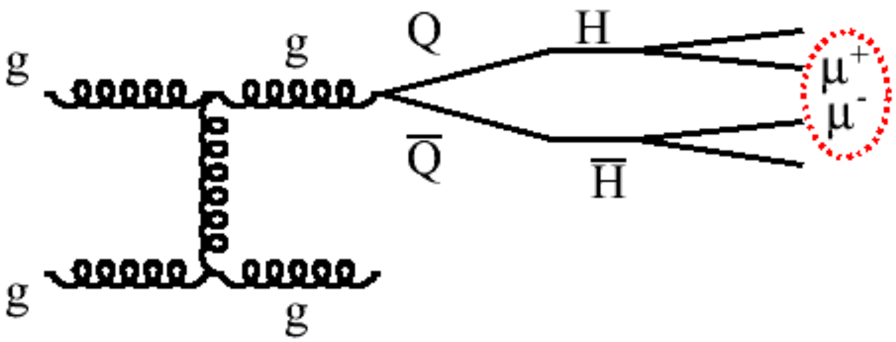
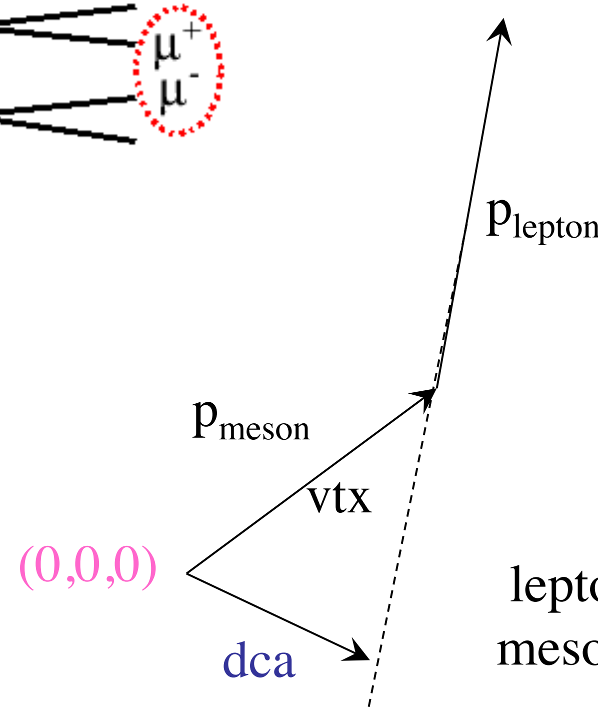


Fig. 5.1 Fragmenting parton probability for Z^0-tagged jets as function of the transverse momentum

Displaced Track Study for Background Reduction

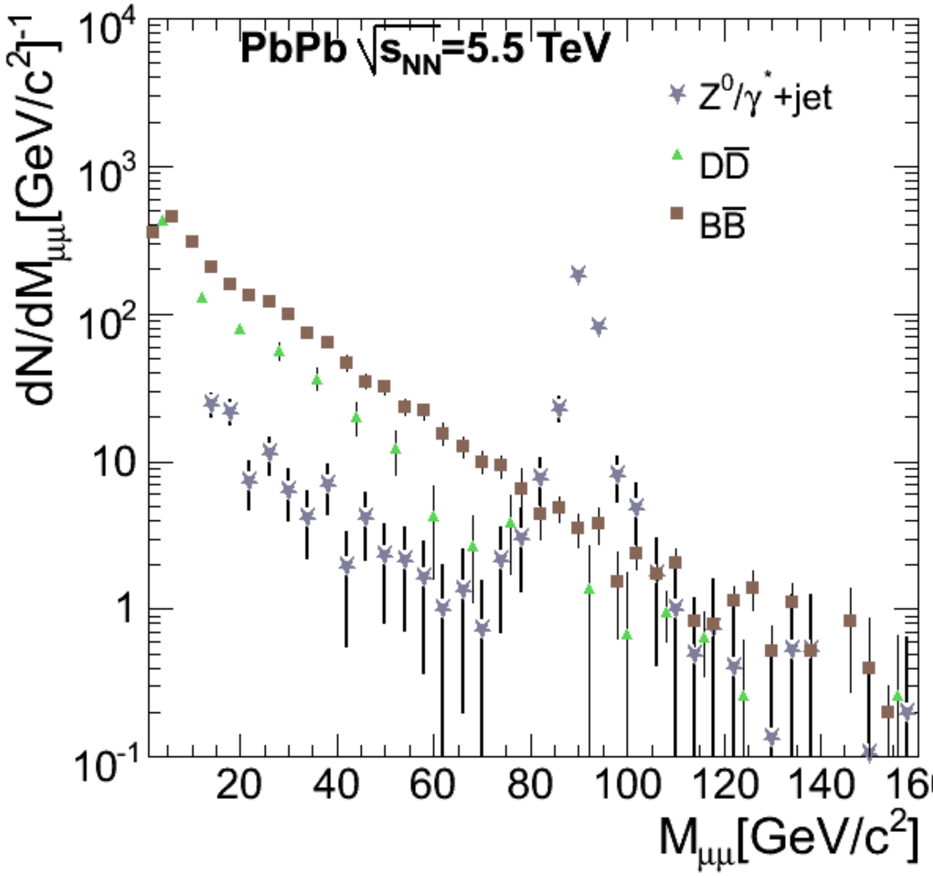




lepton = $e^{\pm}$, $\mu^{\pm}$
meson = $D^{\pm}$, $B^{\pm}$

- CMS experiment has a powerful vertex detectors, resolution of about 50 micron

LANL Studies - Z^0

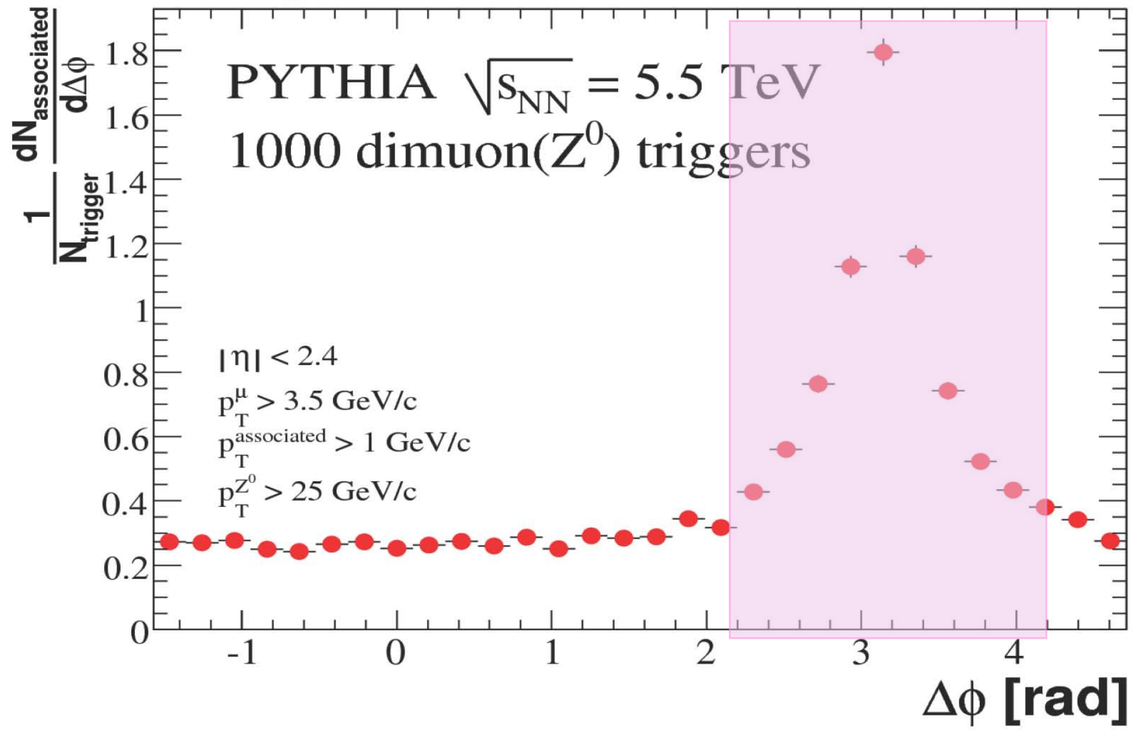


Invariant mass distribution for Z^0/γ^* and DDbar/BBbar dimuons. $p_T^{dimuon}>25GeV/c$, $p_T^{muon}>3.5$ GeV/c and $|\eta^{muon}|<2.4$ An integrated luminosity of 0.5 nb^{-1} is assumed.

- Signal and heavy quark background

LANL Studies

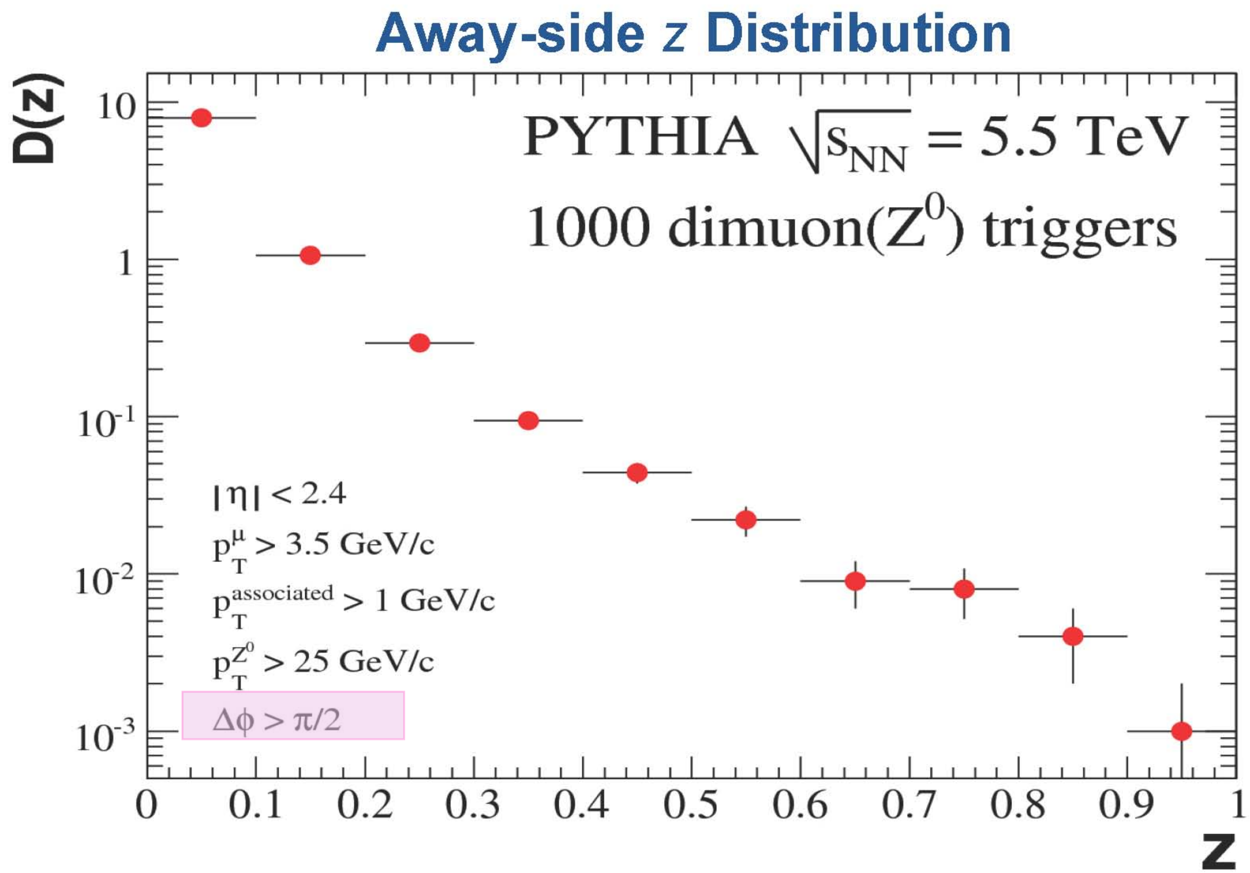
Trigger-Associated ΔΦ Distribution



Relative azimuthal angle between trigger dimuon and associated charged hadron for $p_T^{trigger}$>25GeV/c and $p_T^{associated}$>1 GeV/c, p_T^{muon}>3.5 GeV/c and $|\eta^{muon}|$<2.4 . A sample of 1000 Z^0 dimuon triggers was used.

This is not yet scaled for Pb-Pb

LANL Studies



The number of associated charged hadrons ($\Delta\Phi > \pi/2$) per trigger dimuon as a function of their momentum fraction z for $p_T^{dimuon} > 25$GeV/c and $p_T^{associated} > 1$ GeV/c, $p_T^{muon} > 3.5$ GeV/c and $|\eta^{muon}| < 2.4$.
The statistical error bars reflect a sample of 1000 Z^0 dimuon triggers.

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Estimate of "in-medium fragmentation function " measurement

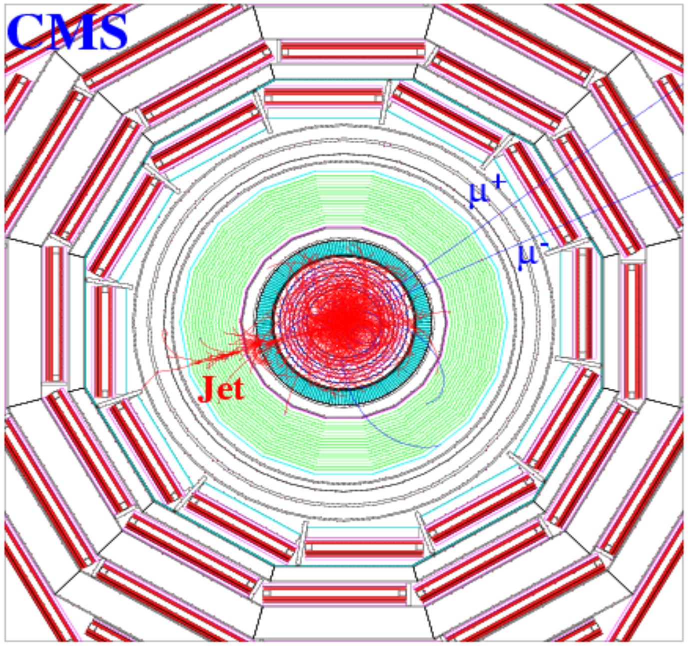
Physics & T theoretical division

Gerd J. Kunde

EM-Hadron Correlations Summary

Z+jet event in the Heavy Ion collision

dNch / dY = 5000



Pt(Z) = Et(Jet) = 100 GeV.

- Z^0 is a weakly interacting probe to analyze the strongly interacting matter at LHC
- The dilepton trigger gives direct and accurate access to the initial momentum of the away-side jet
- The Z^0 dimuon tagged jets are a clean signal that can be measured to high momentum

- **Reasonable rates to try a measurement of the fragmentation function in Pb-Pb collisions**

The “Barnes”-Report on Heavy-Ion Physics

U.S. Program in Heavy-Ion Nuclear Physics: Scientific Opportunities and Resource Requirements

Report of the NSAC Subcommittee Review of Heavy-Ion Nuclear Physics

Peter D. Barnes, Richard F. Casten, Kees de Jager, Bradley Filippone , Carl Gagliardi, Thomas Glasmacher, Hans-Ake Gustafsson , Ulrich Heinz, Barbara Jacak, Peter Jacobs , John M. Jowett, Alfred H. Mueller, Urs Wiedemann

“The heavy-ion physics program beginning at the LHC in 2008, will become the new heavy-ion high energy frontier and has high discovery potential as a result of a factor of 30 increase in the center-of-mass energy relative to RHIC. ……. The Subcommittee ***strongly supports*** *a continuation of a vigorous program at RHIC and* ***the development of U.S. participation in the Heavy-Ion program at the LHC.***

Recommendation #2:
The LHC will open up a new regime in relativistic heavy-ion physics with significant opportunities for new discoveries. The Subcommittee recommends that:

- ***Participation at the LHC should become a new component of the U.S. Heavy- Ion program;***
- ***This participation should receive comparable investment priority with each of the two near-term upgrade programs for the two large RHIC detectors.”***

Implemented in ER20060471 “A New Probe for the Quark Gluon Plasma

Implemented in ER20090303 “ First Unambiguous Measurement of Jet Fragmentation and Energy Loss in the Quark-Gluon-Plasma ”

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plus these address the physics division capability report by focusing at the LHC

What the Experimentalists did …

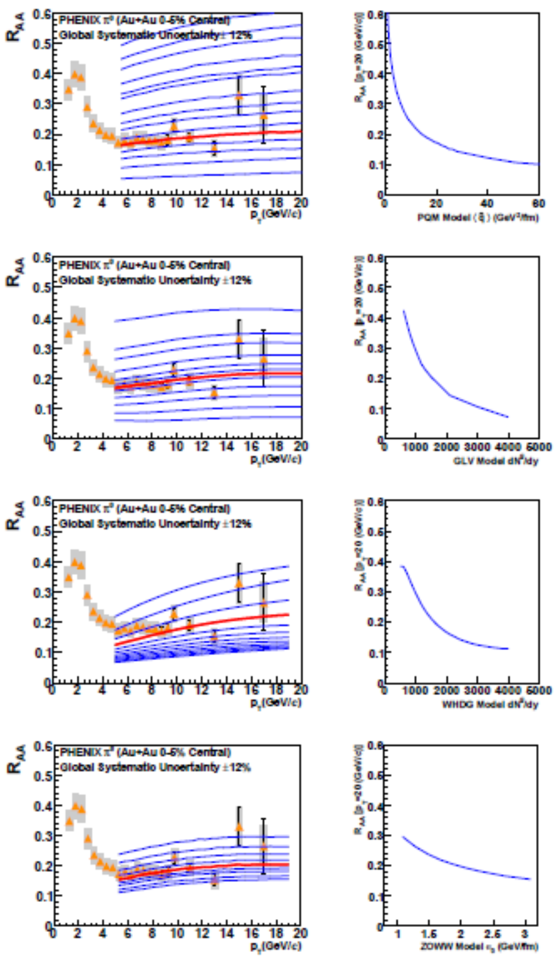

FIG. 2: (Color online) Left panels show π^0 R_{AA} for 0-5% Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV and predictions from PQM [4], GLV [12], WHDG [6], and ZOWW [7] models with (from top to bottom) $\langle\hat{q}\rangle$ values of 0.3, 0.9, 1.2, 1.5, 2.1, 2.9, 4.4, 5.9, 7.4, 10.3, 13.2, 17.7, 25.0, 40.5, 101.4 GeV^2/fm; dN^g/dy values of 600, 800, 900, 1050, 1175, 1300, 1400, 1500, 1800, 2100, 3000, 4000; dN^g/dy values of 500, 800, 1100, 1400, 1700, 2000, 2300, 2600, 2900, 3200, 3500, 3800; and ϵ_0 values of 1.08, 1.28, 1.48, 1.68, 1.88, 2.08, 2.28, 2.68, 3.08 GeV/fm. Red lines indicate the best fit cases of (top) $\langle\hat{q}\rangle$= 13.2, (upper middle) dN^g/dy = 1400, (lower middle) dN^g/dy = 1400, and (bottom) ϵ_0 = 1.88 GeV/fm. Right panels show R_{AA} at p_T = 20 GeV/c.

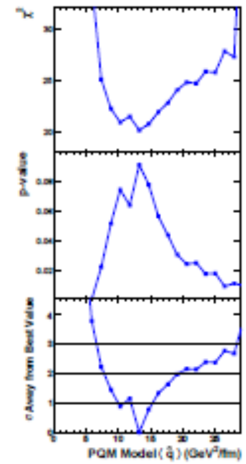

FIG. 4: (Color online) The statistical analysis results from the comparison of the PQM model with the π^0 $R_{AA}(p_T)$ experimental data. The top panel shows the modified $\tilde{\chi}^2$ for different values of the PQM $\langle\hat{q}\rangle$. The middle panel shows the computed p-value directly from the modified $\tilde{\chi}^2$ as shown above. The bottom panel shows the number of standard deviations (σ) away from the minimum (best) $\langle\hat{q}\rangle$ parameter value for the PQM model calculations.

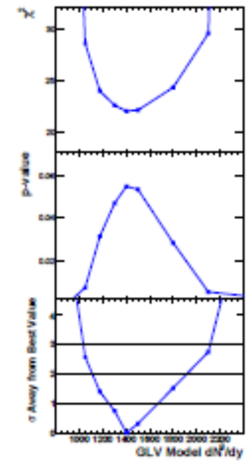

FIG. 5: (Color online) The statistical analysis results from the comparison of the GLV model with the π^0 $R_{AA}(p_T)$ experimental data. The top panel shows the modified $\tilde{\chi}^2$ for different values of the GLV dN^g/dy. The middle panel shows the computed p-value directly from the modified $\tilde{\chi}^2$ as shown above. The bottom panel shows the number of standard deviations (σ) away from the minimum (best) dN^g/dy parameter value for the GLV model calculations.

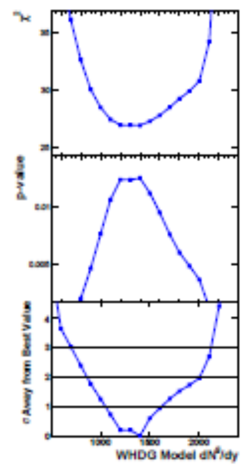

FIG. 6: (Color online) The statistical analysis results from the comparison of the WHDG model with the π^0 $R_{AA}(p_T)$ experimental data. The top panel shows the modified $\tilde{\chi}^2$ for different values of the WHDG dN^g/dy. The middle panel shows the computed p-value directly from the modified $\tilde{\chi}^2$ as shown above. The bottom panel shows the number of standard deviations (σ) away from the minimum (best) dN^g/dy parameter value for the WHDG model calculations.

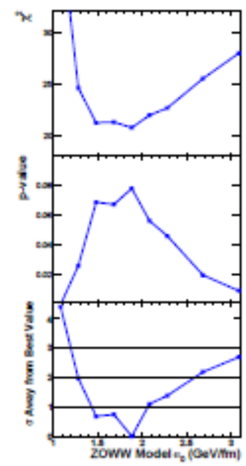

FIG. 7: (Color online) The statistical analysis results from the comparison of the ZOWW model with the π^0 $R_{AA}(p_T)$ experimental data. The top panel shows the modified $\tilde{\chi}^2$ for different values of the ZOWW ϵ_0. The middle panel shows the computed p-value directly from the modified $\tilde{\chi}^2$ as shown above. The bottom panel shows the number of standard deviations (σ) away from the minimum (best) ϵ_0 parameter value for the ZOWW model calculations.

The Transport Coefficient is only Known Within a Factor of Ten !

TABLE II: Quantitative constraints on the model parameters from the PQM, GLV, WHDG, and ZOWW models and a linear functional form fit.

Model Name	Model Parameter	One Standard Deviation Uncertainty	Two Standard Deviation Uncertainty	Maximum p-value
PQM	$\langle \hat{q} \rangle = 13.2$ GeV^2/fm	$+2.1$ -3.2	$+6.3$ -5.2	9.0%
GLV	$dN^g/dy = 1400$	$+270$ -150	$+510$ -290	5.5%
WHDG	$dN^g/dy = 1400$	$+200$ -375	$+600$ -540	1.3 %
ZOWW	$\epsilon_0 = 1.9$ GeV/fm	$+0.2$ -0.5	$+0.7$ -0.6	7.8 %
Linear	b (intercept) = 0.168	$+0.033$ -0.032	$+0.065$ -0.066	11.6%
	m (slope) = 0.0017 (c/GeV)	$+0.0035$ -0.0039	$+0.0070$ -0.0076	

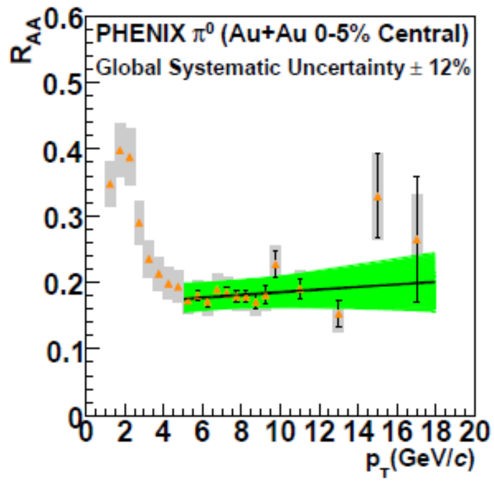

FIG. 8: (Color online) The π^0 nuclear suppression factor R_{AA} as a function of transverse momentum for 0-5% Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV. Point-to-point uncorrelated statistical and systematic uncertainties are shown as uncertainty bars. Correlated systematic uncertainties are shown as gray boxes around the data points. The global scale factor systematic uncertainty is quoted as text. Also shown are the best fit and the envelope of lines with one standard deviation uncertainty for a simple linear fit function constrained by the statistical and systematic uncertainties.

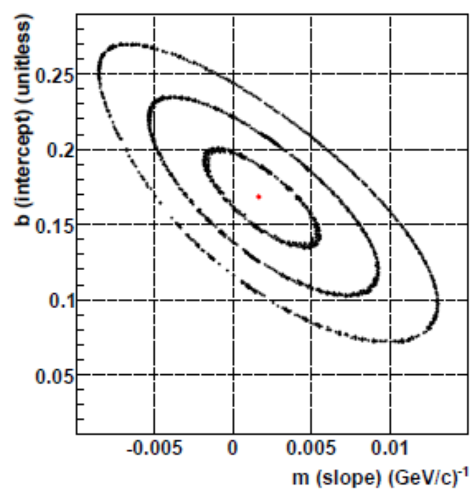

FIG. 9: (Color online) Shown are the best fit values for m(slope) and b(intercept) as constrained by the experimental data. Also shown are the one, two and three standard deviation uncertainty contours.

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Physics & T division

Gerd J. Kunde

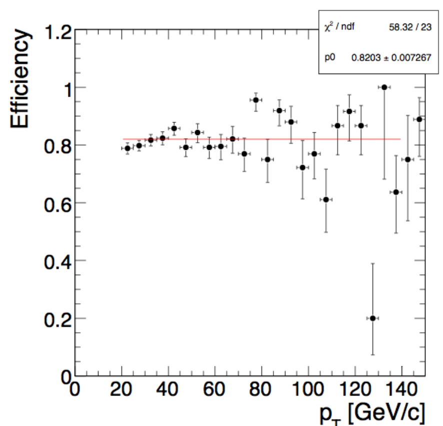
DOE/LANL Missions

- Scientific discovery
  - The Large Hadron Collider is the most advanced and sophisticated discovery machine mankind ever developed.
  - The questions addressed are the most fundamental questions in physics and range from the origin of mass to the properties of the quark-gluon plasma.
  - The National Research Council identified the quark-gluon plasma properties as one of the 10 science questions for the new century.
  - We address in our research the opacity of the plasma, one of its defining properties.

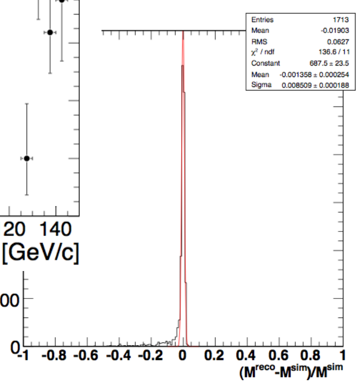
Background and Significance

- Impact of the work:
  - "Z^0-tagging of jets" will be a fundamentally new measurement (developed by LANL) that in conjunction with the theory development will yield the most accurate QGP measurement so far.
  - Developing the electronic components for the experiment ties directly into strategic missions of LANL, such as ISR needs.
- Current efforts:
  - The work is adding important new insights to the discoveries at RHIC (PHENIX team), the tagged jets are measurements that can only be performed at the LHC and LANL is leading the Z^0 and E_T efforts in CMS HI.
- Relevance to LANL missions
  - Large scale and grid computing plus object oriented programming
  - Technical competence in high speed electronics systems with FPGAs and cross point switches
  - Development of future electronics application using the latest circuitry developments

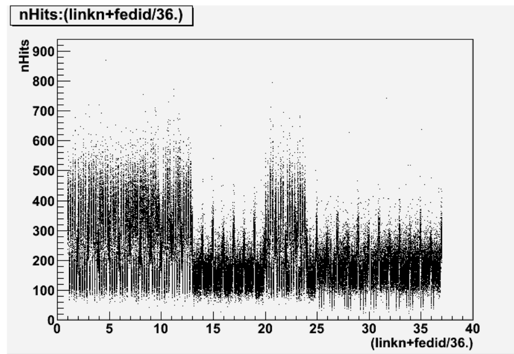
Results in Exp. and Theory



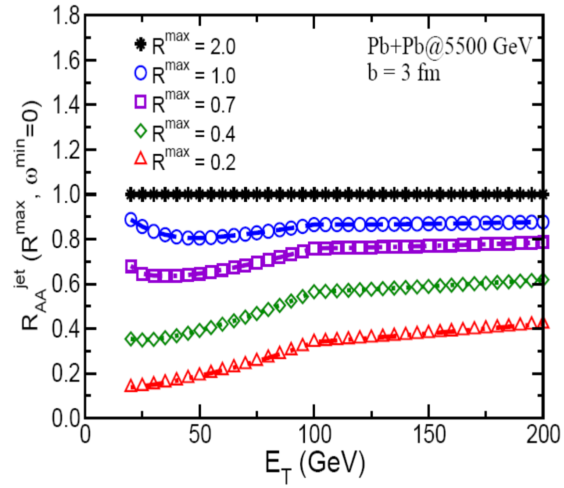
Dimuon Efficiency



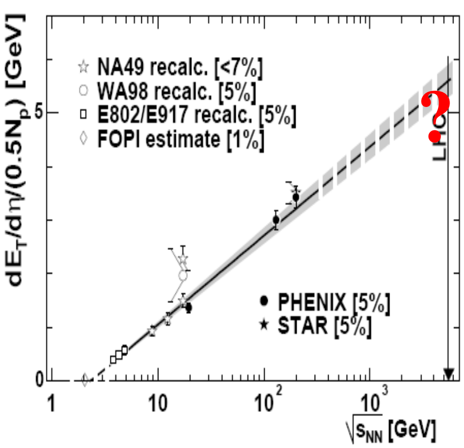
Z Mass Resolution

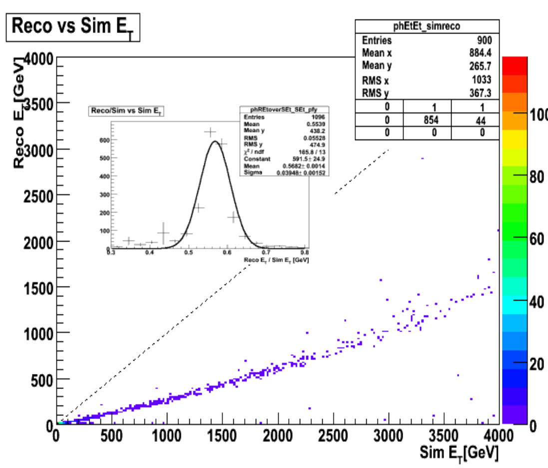


Pixel Fed Link Occupancy

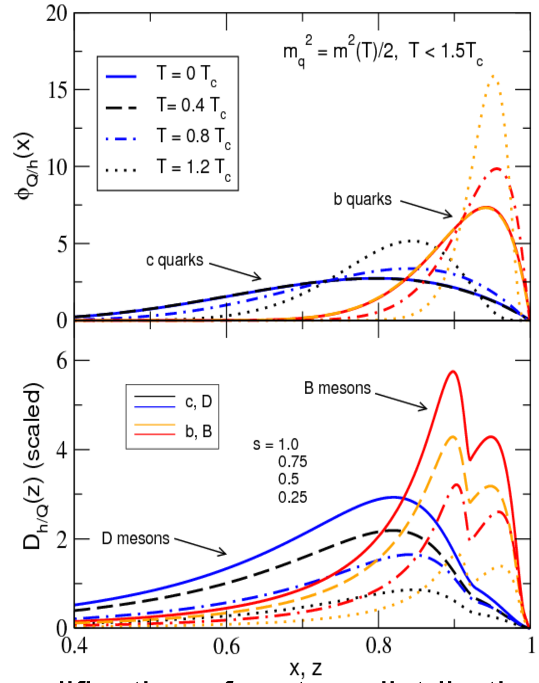


Suppression of the jet cross section in Pb+Pb collisions at the LHC vs E_T and R





Transverse Energy Measurement using the CMS Tracker



In-medium modification of parton distribution and fragmentation functions at non-zero temperature

The Paper Abstracts

Z^0-tagged quark jets at the large hadron collider

G.J. Kunde[a], H. van Hecke, K. Hessler, C. Mironov
Physics Division, Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM 87506, USA

Received: 8 October 2008 / Revised: 2 February 2009 / Published online: 27 February 2009

Abstract The Large Hadron Collider will allow studies of hard probes in nucleus-nucleus collisions which were not accessible at the Relativistic Heavy Ion Collider—even the study of small cross-section Z^0-tagged jets becomes possible. Going beyond the measurement of back-to-back correlations of two strongly interacting particles to measure plasma properties, we replace one side by an electromagnetic probe which propagates through the plasma undisturbed and therefore provides a measurement of the energy of the initial hard scattering. We show that at sufficiently high transverse momentum the Z^0-tagged jets originate predominately from the fragmentation of quarks and anti-quarks while gluon jets are suppressed. We propose to use lepton-pair tagged jets to study medium-induced partonic energy loss and to measure in-medium parton fragmentation functions to determine the opacity of the quark gluon plasma.

PACS 12.38Mh · 25.75Nq

Dilepton-tagged $Q\overline{Q}$ + jet events at the LHC

Camelia Mironov[1,a], Ramona Vogt[2,3], Gerd J. Kunde[1]
[1]Los Alamos National Laboratory, PO Box 1663, Los Alamos, NM, USA
[2]Lawrence Livermore National Laboratory, PO Box 808, Livermore, CA, USA
[3]Physics Department, UC Davis, Davis, CA, USA

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Abstract We propose a new method for identifying and isolating $Q\overline{Q}$ + jet events through semileptonic decays of the $Q\overline{Q}$ pair. Employing these decay dileptons to tag the jet in a specific kinematic region provides a clean signature of jets associated with heavy-quark production. The measurement, in both pp and heavy-ion collisions, is essential for addressing heavy-quark fragmentation in vacuum and in a dense medium. We present next-to-leading order calculations of $Q\overline{Q}$ production (leading order in $Q\overline{Q}$ + jet production) in $\sqrt{s} = 14$ TeV pp collisions at the LHC and discuss the feasibility of the measurement in heavy-ion collisions at $\sqrt{s_{NN}} = 5.5$ TeV.

PACS 13.87.Ce · 24.85.+p · 25.75.Cj · 12.38.Qk

A light-front wavefunction approach to heavy quark fragmentation in the QGP

Rishi Sharma[1,*] Ivan Vitev[1,†] and Ben-Wei Zhang[1,2‡]
[1] *Los Alamos National Laboratory, Theoretical Division, Los Alamos, NM 87545, USA and*
[2] *Institute of Particle Physics, Central China Normal University, Wuhan, 430079, China*

We calculate the charm and beauty fragmentation functions in the vacuum using their operator definitions in factorized perturbative QCD and find leading corrections that arise from the structure of the final-state hadrons. In the framework of potential models we demonstrate the existence of open heavy flavor bound states in the QGP in the vicinity of the critical temperature and provide first results for the in-medium modification of the heavy quark distribution and decay probabilities in a co-moving plasma. In an improved perturbative QCD description of heavy flavor dynamics in the thermal medium we combine D and B meson formation and dissociation with parton-level charm and beauty quark quenching to obtain predictions for the heavy meson and non-photonic electron suppression in Cu+Cu and Pb+Pb collisions at RHIC and the LHC, respectively.

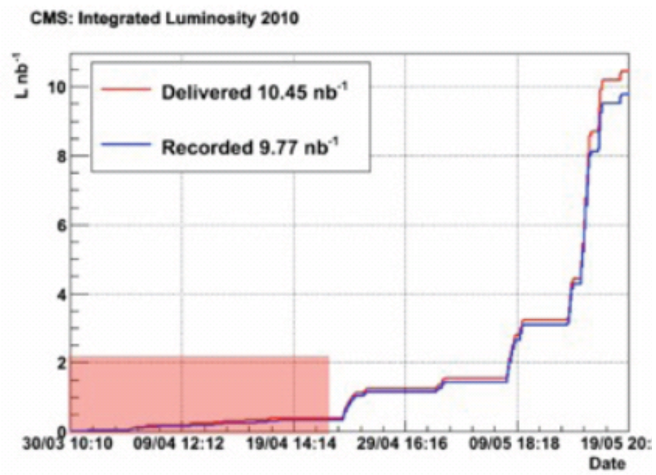
PACS numbers: 24.85.+p; 25.75.-q; 12.38.Mh

A theory of jet shapes and cross sections: from hadrons to nuclei

Ivan Vitev,[1] Simon Wicks,[2] and Ben-Wei Zhang[1,3]
[1]*Los Alamos National Laboratory, Theoretical Division, MS B238, Los Alamos, NM 87545, USA*
[2]*Department of Physics, Columbia University, 538 West 120-th Street, New York, NY 10027, USA*
[3]*Institute of Particle Physics, Hua-Zhong Normal University, Wuhan, 430079, China*
(Dated: July 6, 2009)

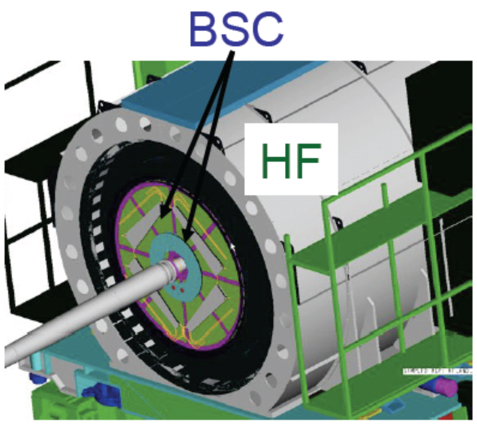
For jets, with great power comes great opportunity. The unprecedented center of mass energies available at the LHC open new windows on the QGP: we demonstrate that jet shape and jet cross section measurements become feasible as a new, differential and accurate test of the underlying QCD theory. We present a first step in understanding these shapes and cross sections in heavy ion reactions. Our approach allows for detailed simulations of the experimental acceptance/cuts that help isolate jets in such high-multiplicity environment. It is demonstrated for the first time that the pattern of stimulated gluon emission can be correlated with a variable quenching of the jet rates and provide an approximately model-independent approach to determining the characteristics of the medium-induced bremsstrahlung spectrum. Surprisingly, in realistic simulations of parton propagation through the QGP we find a minimal increase in the mean jet radius even for large jet attenuation. Jet broadening is manifest in the tails of the energy distribution away from the jet axis and its quantification requires high statistics measurements that will be possible at the LHC.

QCD Studies or The p-p Baseline at the LHC



Integrated luminosity at 7 TeV ~ 10 nb^{-1}

- Trigger:
  - Single hit BSC
  - In-time with BPTX
- Offline:
  - 1 tower with >3 GeV in each HF (forward calo)
  - Beam-halo rejection from BSC timing
  - Vertex from pixel track(s)



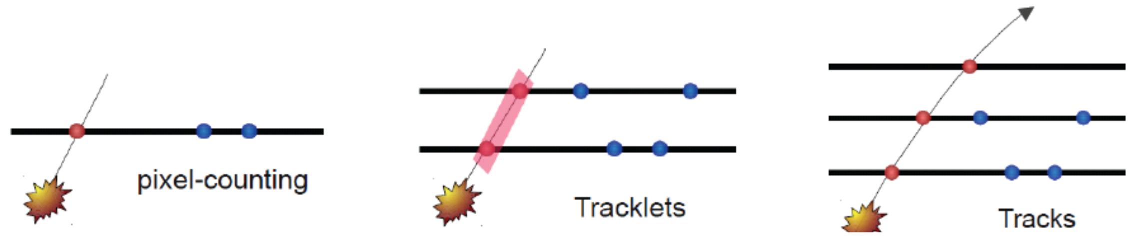
BSC: $3.23 < |\eta| < 4.65$

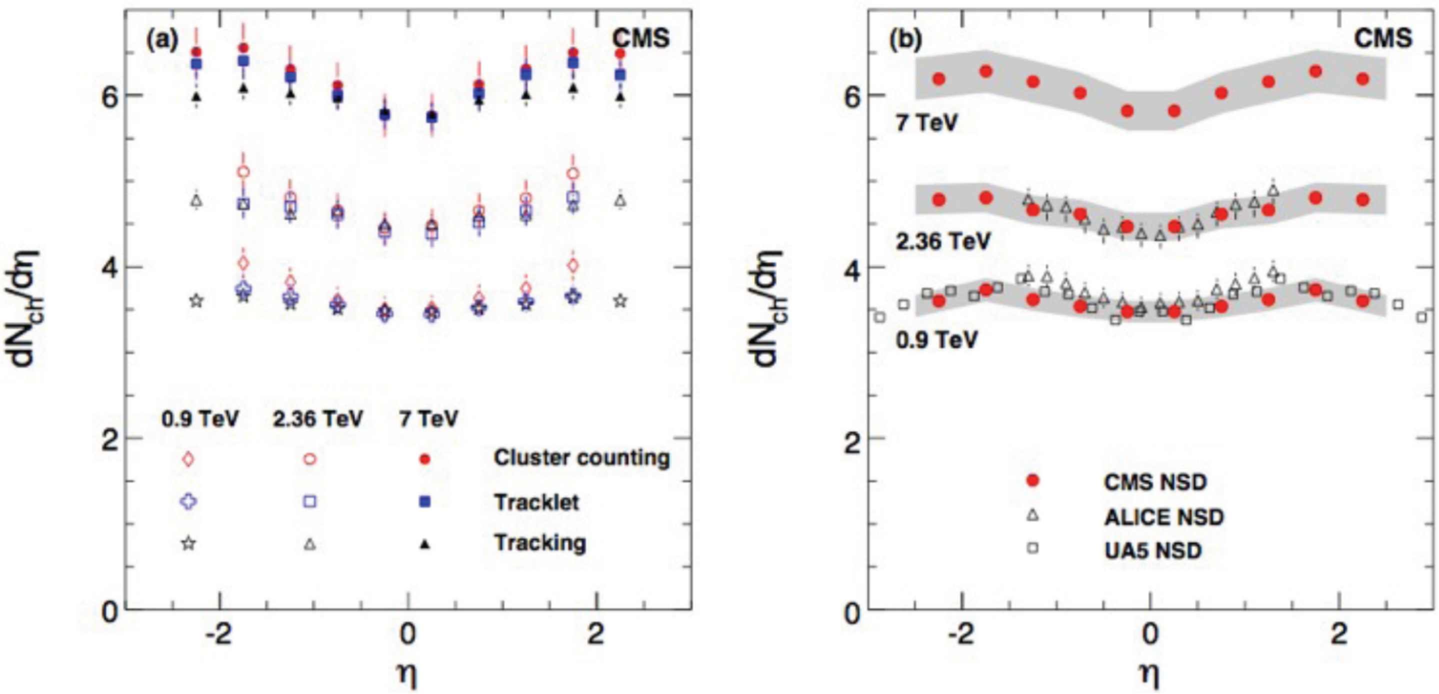
HF: $2.9 < |\eta| < 5.2$

- p-p collisions at 0.9, 2.36 and 7 TeV
- First measurements performed with 10,000 to 200,000 minimum bias events

Charged Particle Multiplicities in p-p

Three Methods

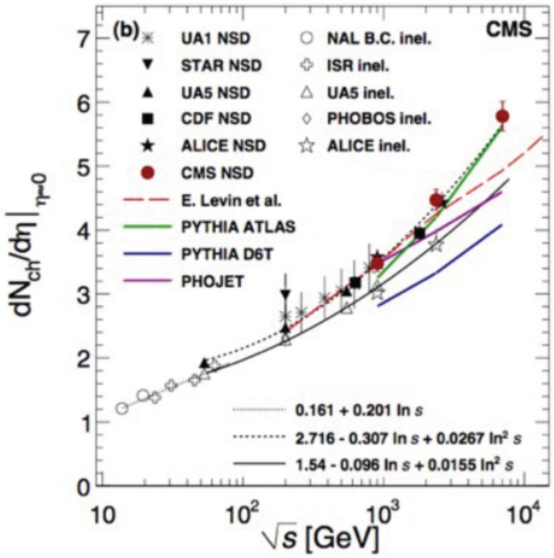


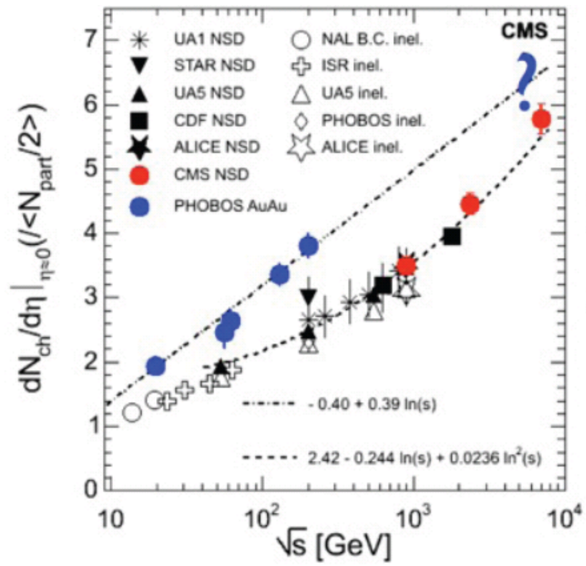


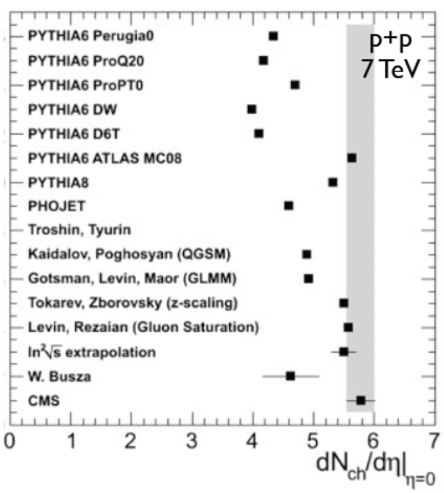
Phys. Rev. Lett. 105, 022002 (2010)

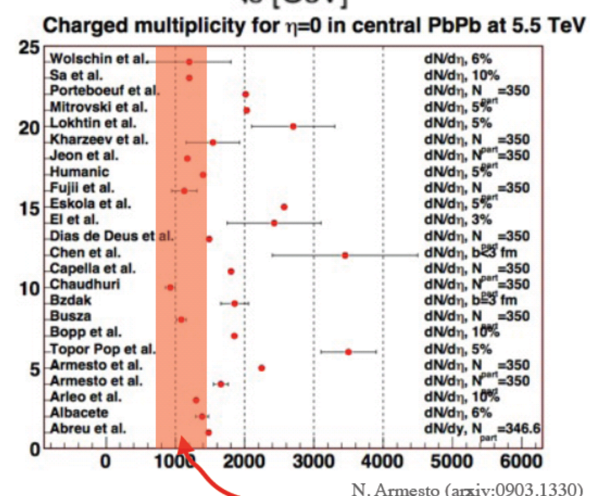
Different systematic errors for each measurement; final result are weighted by uncorrelated errors, averaged and symmetrized

Collision Energy Dependence and Implications for Heavy Ion Collisions





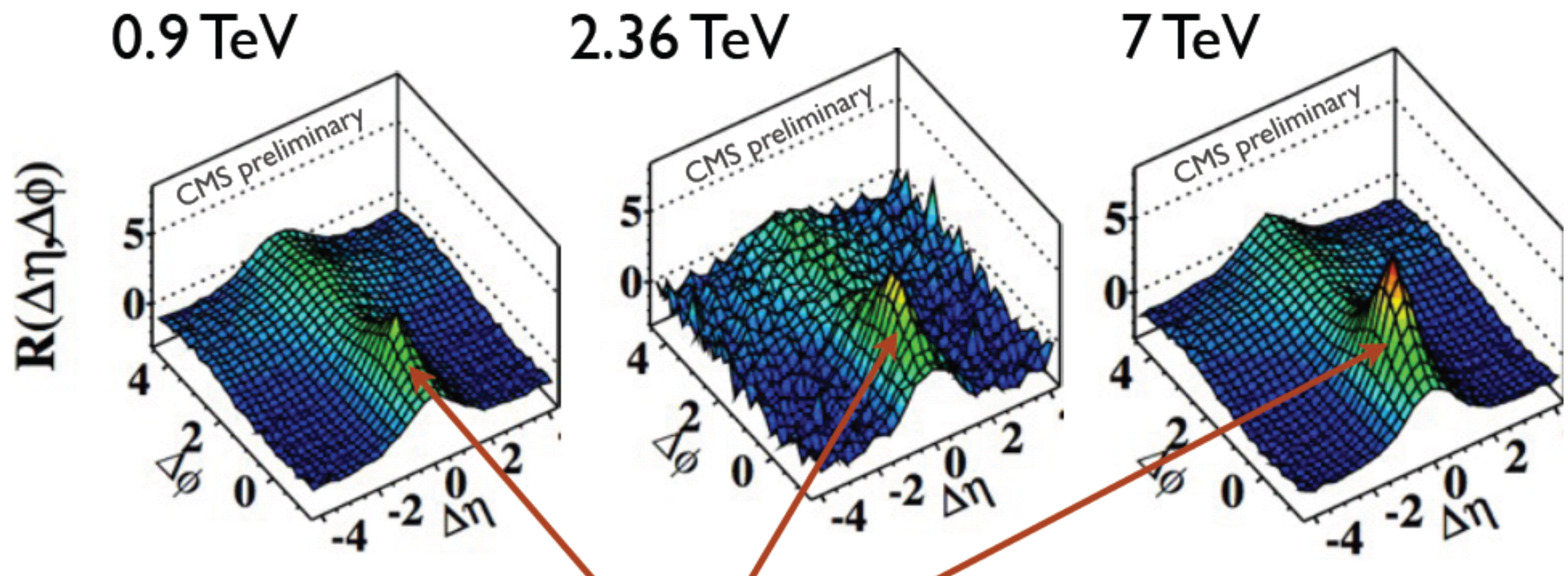




High end of predictions in pp - unlikely regime for HI ?

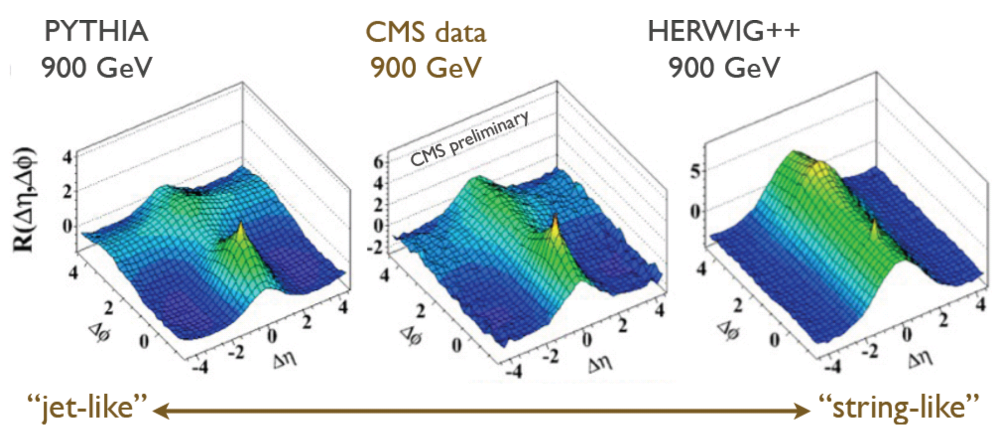
First Correlation Results for p-p

$$R(\Delta\eta,\Delta\phi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\phi)}{B_N(\Delta\eta,\Delta\phi)} - 1\right)\right\rangle_N$$

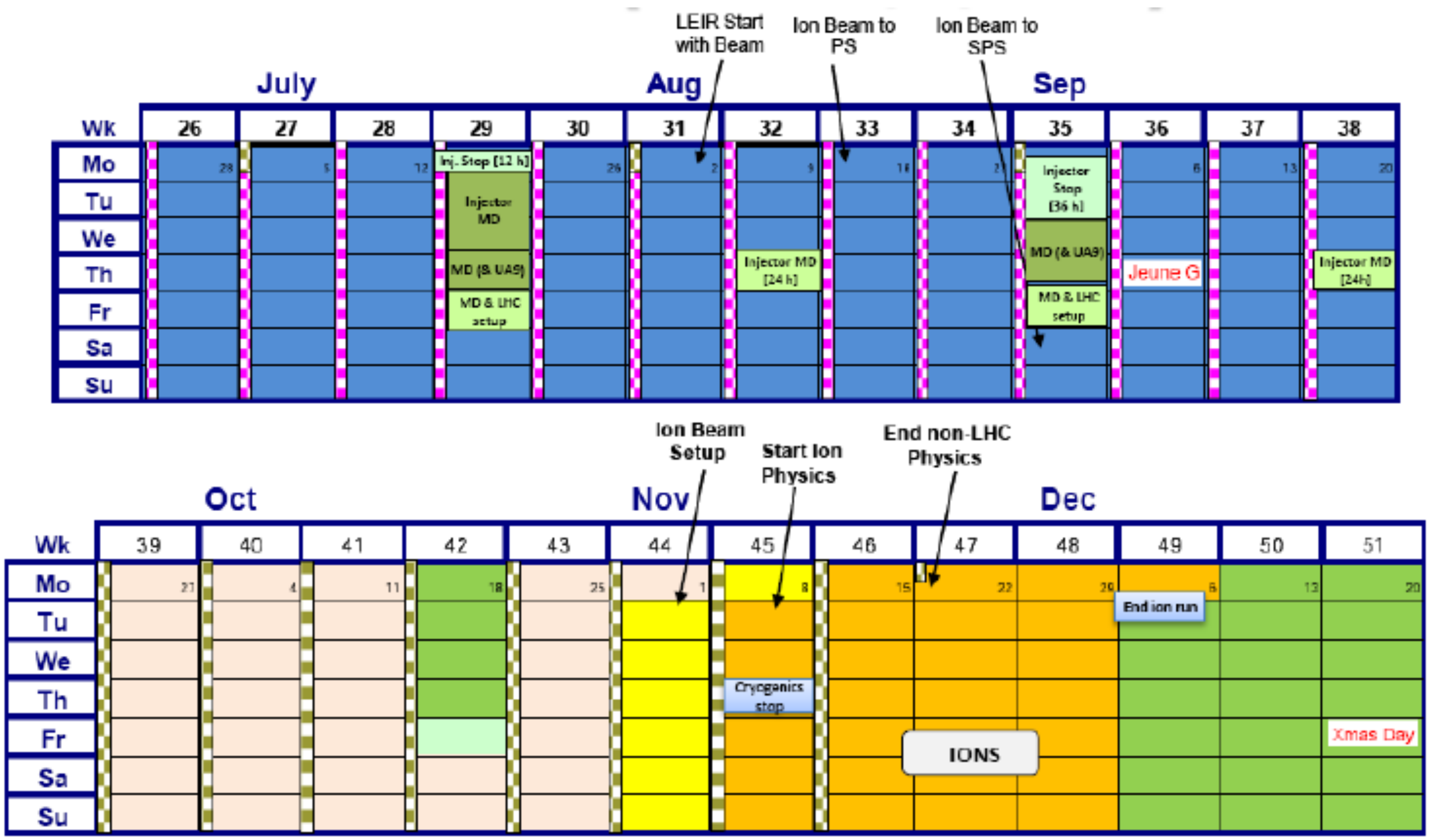


Rapid growth of "jet-like" component with $\sqrt{s}$

Qualitative Model Comparison



The Heavy Ion Run - Schedule



Lead-up to lead in LHC involves a lot of work in the ion injectors, especially SPS

- Technical Stop
- Recommissioning with beam
- SPS et al - physics
- Ion run
- Ion setup

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winter 2010 / winter 2011 / 2013 (high luminosity)

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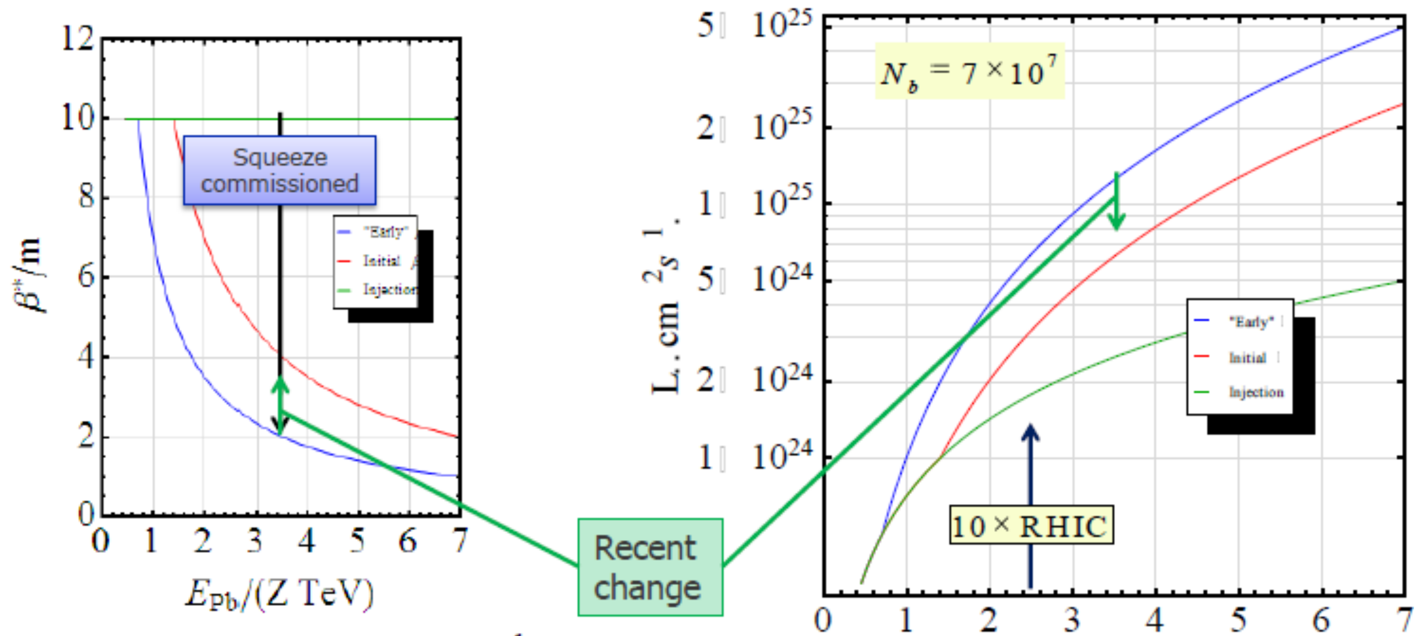
Physics & T division

The Luminosity for the First Two Runs

Potential peak ion luminosity



Triplet aperture limit scaling: $\beta^* \propto \dfrac{1}{E_p}$

$$\beta^*(E_p) = \begin{cases} \min(1.7/E_p, 10.) & \mathrm{m} & \text{"Early"} \\ \min(3.5/E_p, 10.) & \mathrm{m} & \text{Initial} \\ 10. & \mathrm{m} & \text{Injection} \end{cases} \Rightarrow L = \frac{k_b N_b^2 f_0}{4\pi\sigma^{*2}} \propto \frac{E_p}{\beta^*}$$

$10^{25}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} = 0.864\ \mu\mathrm{b}^{-1}\mathrm{day}^{-1}$

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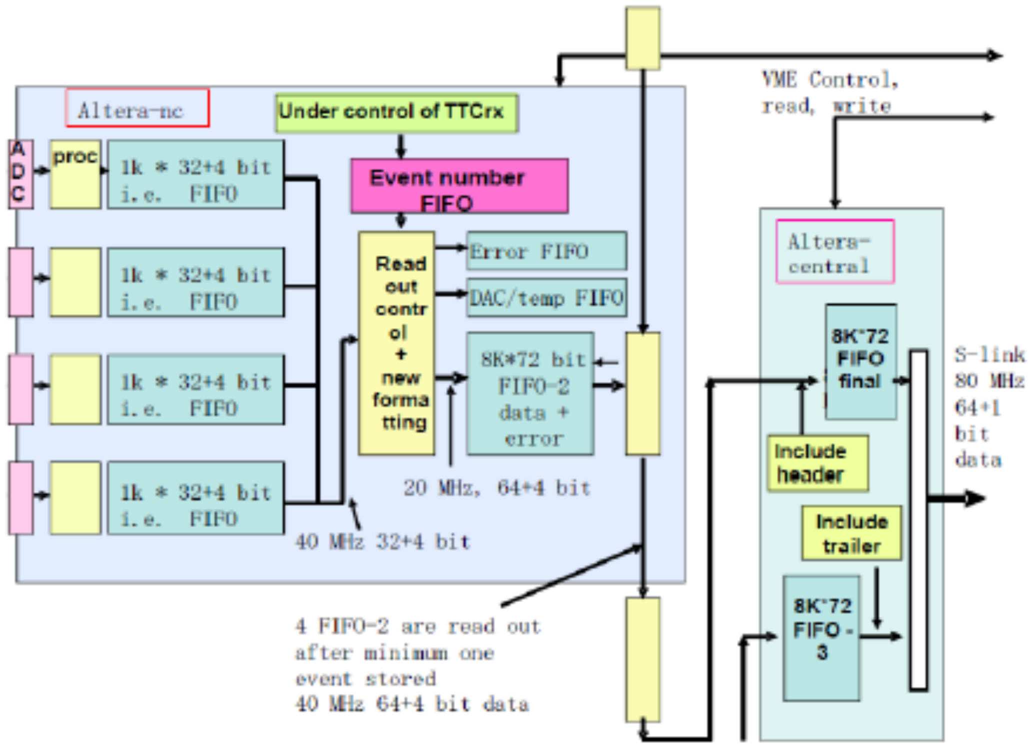
In 2010: integrated luminosity 3-10 μb^{-1} -> Several hundred Z^0

FED Current Readout Scheme



- The four FIFOs are read filled in parallel (6 cycles/hit) and then read out in sequence (1 cycle/hit)
- Vienna is working on parallel read scheme, if successful then new problem solution could be possible -> next slide